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Motion camouflage in a stochastic setting

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***Abstract*— Recent work has formulated 2- and 3-dimensional models and steering control laws for motion camouflage, a stealthy pursuit strategy observed in nature. Here we extend the model to encompass the use of a high-gain pursuit law in the presence of sensor noise as well as in the case when the evader's steering is driven by a stochastic process, demonstrating (in the planar setting) that motion camouflage is still accessible (in the mean) in finite time. We also discuss a family of admissible stochastic evader controls, laying out the groundwork for a future game-theoretic study of optimal evasion strategies.**

I. INTRODUCTION

Motion camouflage is a stealthy pursuit strategy which relies on minimizing the perceived relative motion of a pursuer as observed by its prey. The phenomenon of motion camouflage has been biologically documented for visual insects in [16] and in [11] (based on [2]), mathematically characterized (e.g., [4]), and recently analyzed as a deterministic feedback system [9], [13]. Furthermore, a geometrically indistinguishable strategy has been shown to be used by certain echolocating bats intercepting prey insects [3]. The analysis of a feedback law for motion camouflage has been performed in both the planar ([9]) and three-dimensional settings ([13]), using the machinery of curves and moving frames [1]. Close parallels have been shown to exist between motion camouflage (which is rooted in biology), and the Pure Proportional Navigation Guidance (PPNG) law for missile guidance [12], [15]. That motion camouflaged pursuit appears in such diverse contexts has motivated more detailed study of such aspects as sensory feedback delays [14], and the stochastic formulation presented in the present work.

Previous work in [9] and [13] made use of natural Frenet frames [1] to describe the particle trajectories and develop models for the pursuer-evader interaction in a deterministic setting. In this paper we make use of the planar model to investigate the impacts of stochasticity such as sensor noise and evader controls driven by random processes. In the biological setting, we consider possible connections with organisms that appear to use stochastic control processes, such as the "run-and-tumble" movement exhibited in bacterial chemotaxis (see, e.g., [17]). Many species of bacteria use this type of stochastic steering control, which we model as a continuous time, finite state (CTFS) process driven by Poisson counters. (See Section V). Other types of erratic evasion maneuvers utilized by a variety of insects, birds and fish are discussed in [5]. In the vehicular setting, we note possible applications in areas such as aircraft-missile interactions, considering the possibility that some type of stochastic evasive maneuver may in fact prove most effective against an inbound weapon. (We do not consider such issues in the current paper but plan to address the game-theoretic problem in future work.)

We proceed by sketching the planar pursuit-evasion model as well as some of the fundamentals of motion camouflage and the motion camouflage proportional guidance (MCPG) feedback law derived in [9]. In Section III we consider the effects of sensor noise, and in Section IV we address motion camouflage with a stochastically steering evader, stating and proving a proposition that the MCPG law will still ensure attainment of motion camouflage in the mean in finite time. After presenting some specific forms of admissible stochastic controls in Section V and simulation results in Section VI, we conclude by discussing directions for future work.

II. MOTION CAMOUFLAGE MODEL

Our starting point is the deterministic planar motion camouflage model described in [9]. A generalization of this deterministic planar model may be found in [13], and the analysis presented here can be generalized to three dimensions using the same techniques. Because here we wish to focus on the novel stochastic elements being introduced into the motion camouflage model, we restrict discussion to the planar setting. Also, to streamline the discussion we assume constant-speed motion and no sensorimotor feedback delays.

A. Trajectory and frame evolution

To keep the discussion as self-contained as possible, we reiterate the basic planar motion camouflage formulation of [9]. Particles moving at constant speed subject to continuous (deterministic) steering controls trace out trajectories which are C^2, i.e., twice continuously differentiable. Without loss of generality, we may assume that the pursuer particle moves at unit speed, and the evader particle moves at speed $\nu > 0$ (i.e., ν corresponds to the ratio of speeds of the pursuer and evader).

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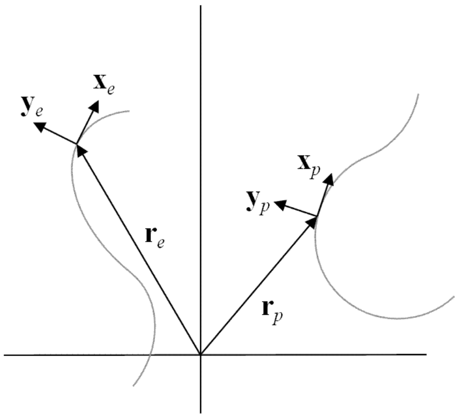

Fig. 1. Illustration of the trajectories and natural Frenet frames for the planar pursuer-evader engagement. (Figure from [9].)

The motion of the pursuer is described by

$$\begin{aligned} \dot{\mathbf{r}}_p &= \mathbf{x}_p, \\ \dot{\mathbf{x}}_p &= \mathbf{y}_p u_p, \\ \dot{\mathbf{y}}_p &= -\mathbf{x}_p u_p, \end{aligned} \tag{1}$$

and the motion of the evader is described by

$$\begin{aligned} \dot{\mathbf{r}}_e &= \nu \mathbf{x}_e, \\ \dot{\mathbf{x}}_e &= \nu \mathbf{y}_e u_e, \\ \dot{\mathbf{y}}_e &= -\nu \mathbf{x}_e u_e, \end{aligned} \tag{2}$$

where the steering control of the evader, u_e, is prescribed, and the steering control of the pursuer, u_p, is given by a feedback law. The orthonormal frame $\{\mathbf{x}_p, \mathbf{y}_p\}$, which is the planar natural Frenet frame for the pursuer particle, evolves with time as the pursuer particle moves along its trajectory (described by $\mathbf{r}_p$). Similarly, $\{\mathbf{x}_e, \mathbf{y}_e\}$ is the planar natural Frenet frame corresponding to the evader particle. (In the planar setting, the natural Frenet frame and the Frenet-Serret frame coincide; however in higher dimensions the distinction is critical [1], [8].)

Here we assume $\nu < 1$, so that the pursuer moves faster than the evader. Figure 1 illustrates (1) and (2). (As noted in [9], the controls u_e and u_p are actually acceleration inputs since they directly drive the angular velocity of the particles. However, the speed for each particle remains constant since the acceleration inputs are constrained to be applied perpendicular to the instantaneous direction of particle motion.)

B. Definition of motion camouflage

In this paper we focus on "motion camouflage with respect to infinity", the strategy in which the pursuer maneuvers in such a way that, from the point of view of the evader, the pursuer always appears at the same bearing. This is described in [9] as

$$\mathbf{r}_p = \mathbf{r}_e + \lambda \mathbf{r}_\infty \tag{3}$$

where $\mathbf{r}_\infty$ is a fixed unit vector and λ is a time-dependent scalar. We define the "baseline vector" as the vector from the evader to the pursuer

$$\mathbf{r} = \mathbf{r}_p - \mathbf{r}_e, \tag{4}$$

and $|\mathbf{r}|$ denotes the baseline length. Restricting ourselves to the non-collision case (i.e. $|\mathbf{r}| \neq 0$), we define $\mathbf{w}$ as the vector component of $\dot{\mathbf{r}}$ which is transverse to $\mathbf{r}$, i.e.

$$\mathbf{w} = \dot{\mathbf{r}} - \left(\frac{\mathbf{r}}{|\mathbf{r}|} \cdot \dot{\mathbf{r}} \right) \frac{\mathbf{r}}{|\mathbf{r}|}. \tag{5}$$

It was demonstrated in [9] that the pursuit-evasion system (1),(2) is in a state of motion camouflage without collision on a given time interval iff $\mathbf{w} = 0$ on that interval.

C. Distance from motion camouflage

The function

$$\Gamma = \frac{\frac{d}{dt}|\mathbf{r}|}{|\frac{d\mathbf{r}}{dt}|} = \left(\frac{\mathbf{r}}{|\mathbf{r}|} \cdot \frac{\dot{\mathbf{r}}}{|\dot{\mathbf{r}}|} \right) \tag{6}$$

describes how far the pursuer-evader system is from a state of motion camouflage [9], [13]. The system is in a state of motion camouflage when $\Gamma = -1$, which corresponds to pure shortening of the baseline vector. (By contrast, $\Gamma = 0$ corresponds to pure rotation of the baseline vector, and $\Gamma = +1$ corresponds to pure lengthening of the baseline vector.) The difference $\Gamma - (-1) > 0$ is a measure of the distance of the pursuer-evader system from a state of motion camouflage.

For (6) to be well defined, we must have $|\mathbf{r}| > 0$ as well as $|\dot{\mathbf{r}}| > 0$. The former requirement is satisfied by assuming that $|\mathbf{r}| \neq 0$ initially, and then analyzing the engagement (for finite time) only until $|\mathbf{r}|$ reaches a value $r_0 > 0$ [9], [13]. The latter condition is ensured by the assumption that $0 < \nu < 1$, since $|\dot{\mathbf{r}}| \geq 1 - \nu$.

D. Feedback law for motion camouflage

We define the notation $\mathbf{q}^\perp$ to represent the vector $\mathbf{q}$ rotated counter-clockwise in the plane by an angle $\pi/2$ [9], [13]. When there is no delay associated with incorporating sensory information, we define our feedback law as

$$u_p = -\mu \left(\frac{\mathbf{r}}{|\mathbf{r}|} \cdot \dot{\mathbf{r}}^\perp \right), \tag{7}$$

where $\mu > 0$ is a gain parameter [9], [13]. However, if there is a delay τ in the incorporation of sensory information, then we substitute $u_p(t-\tau)$ for u_p in equation (1).

Observe that (7) is well defined since, by the discussion in the previous subsection, $|\mathbf{r}| \neq 0$ during the duration of our analysis.

E. Deterministic analysis

The key results for the deterministic motion camouflage feedback system are presented in [9], [13]. These results, particularly the planar result in [9], are the inspiration for the calculations below in Section IV.

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