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Distributed Cooperative Laws for Simultaneous Interception in Ring Coupled Unicycles

Kushal P. Singh[1] and Twinkle Tripathy[2]

Abstract— **This paper presents a distributed guidance law for the simultaneous interception of a stationary target using a group of 'n' heterogeneous pursuers. Under the proposed law, simultaneous interception of the target is guaranteed to happen for any arbitrary initial positions or heading angles of the pursuers. A cyclic communication topology is used in this paper, where every pursuer interacts only with its neighbour. We also determine the necessary conditions to impose a feasible desired impact time. The theoretical results have been illustrated through numerical simulations.**

I. INTRODUCTION

A single pursuer or a centrally controlled system may face challenges such as a 'single point of failure',(where a failure in one part of the system leads to the collapse of the entire system), the need for superior sensing capabilities, etc. In contrast, a multi-agent system distributes tasks across a network, offering improved scalability, robustness, operational efficiency, and resource allocation. For these reasons, we address the issue of simultaneous interception using a group of cooperative autonomous pursuers

Given a group of pursuers, the task can be achieved independently or cooperatively. The works presented in [1]–[6] present independent guidance laws where only a single pursuer is used to achieve the desired time of impact. The authors of [1] present a deviated pursuit-based guidance law to control impact time for intercepting constant velocity targets, whereas to capture a stationary target, authors in [2] assign a virtual leader to convert the real problem into a tracking problem and use a combination of PNG commands with feedback on flight time errors. The authors in [3] present IGC(Integrated Guidance and Control), in which the Line-of-Sight angle value converges in finite time, and then missiles pursue a straight line to intercept the target. The authors of [4] present ITCG(Impact Time Control Guidance), which combines PNG law with feedback on impact time error to control impact time. Sliding mode-based control is used in the works presented in [5] and [6], impact time error is used to design sliding surface in [5] whereas in [6] sliding surface is designed with positive continuous nonlinear function of lead angle.

Cooperative guidance is used in the works presented in [7]–[18] to overcome the problems associated with independent guidance laws. The authors in [7] propose CPN(Cooperative Proportional Navigation) to capture a stationary target, similar to PNG, with only time-varying navigational gain and the authors in [8] propose BPNG(Biased PNG), which uses relative impact time error as feedback to capture the target in a 2-D plane. In contrast, authors in [9] present a similar law to capture the target in 3-D. The authors in [10] also solve simultaneous capture with time-varying delays. Similarly, the authors in [11] solve simultaneous target capture with time delay and introduce switching topologies. The authors in [12] propose two-stage guidance: first, agents reach consensus in finite time, and then they disconnect from each other to pursue the target independently using PNG law. The works in [13]–[17] present the control of both impact time and angle.

In most of the works presented earlier, there are constraints on the pursuer's initial positions, initial heading angles or sometimes both. In [18], we cannot use any arbitrary value of initial heading angles for all the pursuers to achieve simultaneous target interception. Deriving inspiration from the results presented in [18]. Using cyclic communication topology, we propose a distributed guidance law for a group of heterogeneous autonomous pursuers, where simultaneous interception will occur for any arbitrary value of initial positions and initial heading angles. We determine the necessary conditions to impose a feasible desired impact time. We propose using only straight lines and circles because of their ease of design and implementability. The straight lines and circles are used because moving on a straight line requires no control effort, and moving on a circular path requires constant lateral acceleration as an input. We also confirm our claims through simulations.

The paper is structured as follows. Section II presents the problem statement. Section III, the proposed guidance law. Section IV, the simulation results, and Section V concludes the paper.

II. PROBLEM STATEMENT

In this work, we aim to design a distributed guidance law to achieve simultaneous interception of a stationary target using a group of heterogeneous autonomous pursuers in a cyclic pursuit framework. Consider a pursuer i $i \in \{1,2,...,n\}$, in a system of heterogeneous autonomous pursuers, which is modelled as a point mass unicycle and

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[1]Kushal P. Singh is a Research Scholar in the Department of Electrical Engineering, Indian Institute of Technology, Kanpur kushalp20@iitk.ac.in

[2]Twinkle Tripathy is an Assistant Professor in the Department of Electrical Engineering, Indian Institute of Technology, Kanpur ttripathy@iitk.ac.in

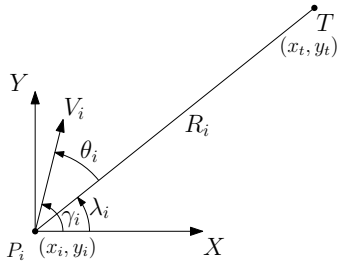


Fig. 1: Basic Engagement Geometry

has the kinematics,

$$\dot{x_i} = V_i \cos\gamma_i \tag{1a}$$
$$\dot{y_i} = V_i \sin\gamma_i \tag{1b}$$
$$\dot{\gamma_i} = a_i / V_i \tag{1c}$$

where P_i is the position of i_{th} pursuer whose coordinates are (x_i, y_i), linear speed V_i which is constant for each pursuer i, lateral acceleration a_i and heading angle γ_i concerning a fixed reference, as shown in Fig. 1. T denotes the position of target and (x_t, y_t) denotes the coordinates of the target. The kinematics of engagement in polar form can be written as

$$\dot{R_i} = -V_i \cos\theta_i \tag{2a}$$
$$\dot{\lambda_i} = \frac{-V_i \sin\theta_i}{R_i} \tag{2b}$$

where R_i is the distance of pursuer i from the target T, λ_i is the line-of-sight angle and θ_i is the lead angle. The next section discusses the guidance law, mathematics, and communication topology used.

III. Cooperative Guidance Law

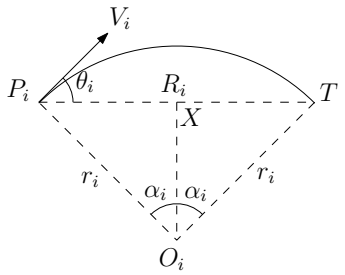


Fig. 2: Circular Trajectory Formation

Consider pursuer i opting for a circular trajectory in reaching the target T as shown in Fig. 2 where r_i and O_i are radius and centre, respectively, of circle followed by pursuer i in pursuing the target. Since V_i is tangent to the circle and TP_iO_i is an isosceles triangle. Therefore, $\alpha_i = \theta_i$. The arc length(say L_i) on a circular path is given by $L_i = angle * radius = 2\alpha_i * r_i = 2\theta_i * r_i$, from geometry we can write $r_i = \frac{R_i}{2\sin\theta_i}$. Therefore, the time pursuer i takes to traverse this circular arc is given by dividing the arc length by linear speed. Thus,

$$\tilde{t_i} = \frac{R_i\theta_i}{V_i \sin\theta_i} \qquad \text{if } 0 < \theta_i < \pi \tag{3a}$$
$$\tilde{t_i} = \frac{R_i(\theta_i - 2\pi)}{V_i \sin\theta_i} \qquad \text{if } \pi < \theta_i < 2\pi \tag{3b}$$

From circular motion, lateral acceleration required is $\frac{v^2}{r}$, where v is linear speed and r is the radius of a circular arc. Therefore, the lateral acceleration pursuer i needs to traverse the circular arc P_iT is

$$a_i{}' = \frac{2V_i{}^2 \sin\theta_i}{R_i}. \tag{4}$$

It is important to note that $\tilde{t_i}$ is the value of time a pursuer takes to reach the target if it takes a circular path from its current position.

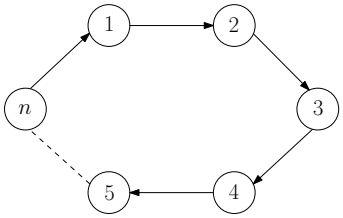


Fig. 3: Cyclic Communication Topology

The communication topology used in this paper is cyclic, shown in Fig.3 is a cyclic communication topology where each pursuer can communicate with only one other pursuer cyclically, i.e. every pursuer can either receive or send data to one neighbour. The control law presented in this paper is for cyclic communication; the motivation for cyclic communication comes from the fact that it is one of the most popular decentralised control methods as it avoids information overload and requires less bandwidth, thus reducing unnecessary time delays. Similarly, this method can be extended to develop guidance laws for other communication topologies as well, some of which are mentioned later in the paper.

Since we want all our n pursuers to strike the target simultaneously, but all pursuers have different speeds, initial locations, and heading angles. So, if they follow a_i' as defined in eqn. (4), all of them will reach the target at different instants. So, next we propose the required guidance law.

To achieve the same impact time, we need to synchronise the impact time of all the pursuers. As the pursuers with larger estimated times of impact($\tilde{t}s$)can not be made to reach early, we must delay the ones that reach early.

$$a_i = 0 \qquad \text{;if } \tilde{t_i} < \tilde{t}_{i+1} \tag{5a}$$
$$a_i = a_i' \qquad \text{;if } \tilde{t_i} \geq \tilde{t}_{i+1} \tag{5b}$$

So, a guidance law has been defined in (5), which ensures this synchronisation. Since moving on a straight line requires no control effort, the delay that is required to achieve synchronisation can be achieved if a pursuer keeps moving on a straight line path.

***Property** 1:* Consider a pursuer j, $j \in \{1, .., n\}$, with kinematics $(1) - (3)$. If a pursuer keeps moving in a straight line

trajectory along its initial heading direction, its impact time $\tilde{t}_j$ is guaranteed to increase eventually.

Proof: Pursuer j requires no control effort to go in a straight line i.e. $a_j{}' = 0$. Also from Fig. 1 we can write $\gamma_j = \theta_j + \lambda_j$, then

$$\dot{\gamma}_j = \dot{\theta}_j + \dot{\lambda}_j \tag{6}$$

In a straight-line path, the heading angle does not change. Therefore, $\dot{\gamma}_j = 0$, this implies $\dot{\theta}_j = -\dot{\lambda}_j$ So,with the help of eqn. (5) we can write

$$\dot{\theta}_j = \frac{V_j \sin\theta_j}{R_j} \tag{7}$$

and from eqn. (4) $\dot{R}_j = -V_j \cos\theta_j$. Now to prove that $\tilde{t}_j$ increases eventually, we observe what happens to $\tilde{t}_j$ when θ varies from 0 to 2π. From eqn (3) we can see that expression for $\tilde{t}$ changes at $\theta_j = \pi$. Therefore first we explain the behaviour of $\tilde{t}_j$ if θ_j is between 0 and π an then for θ_j between π and 2π.

For $\theta_j = 0$ to π, $\dot{\theta}_j > 0$ from (7) i.e. θ_j increases till it approaches π(which can be deduced from geometry of Fig. 1). In this range, the $\tilde{t}_j$ is given by

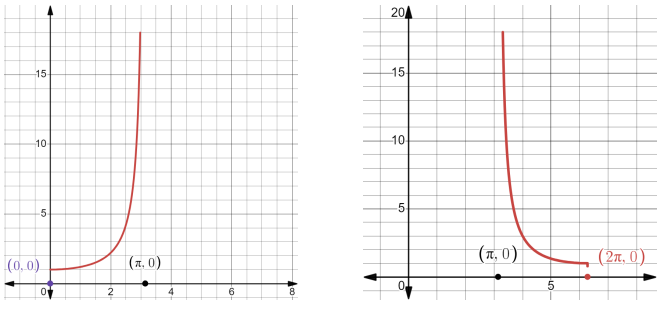
$$\tilde{t}_j = \frac{R_j}{V_j} \frac{\theta_j}{\sin\theta_j}$$

As θ_j tends to π starting somewhere between 0 and π, $\dot{R}_j > 0$ from eqn. 2a, V_j is positive constant and $\frac{\theta_j}{\sin\theta_j}$ is increasing(from Fig. 4a). Therefore, $\tilde{t}_j$ increases eventually if θ_j starts between 0 and π.

For $\theta_j = \pi$ to 2π, $\dot{\theta}_j < 0$ from eqn. (7) i.e. θ_j decreases till it reaches π(which can also be deduced from the geometry of Fig. 1). In this range $\tilde{t}_j$ is given by

$$\tilde{t}_j = \frac{R_j}{V_j} \frac{(\theta_j - 2\pi)}{\sin\theta_j}$$

As θ_j tends to π, starting somewhere between π and 2π, $\dot{R}_j > 0$ from eqn. 2a, V_j is positive constant and $\frac{\theta_j}{\sin\theta_j}$ is increasing(from Fig. 4b). Therefore, $\tilde{t}_j$ increases eventually if θ_j starts between π and 2π. Hence, proved. ■



(a) $\frac{\theta_j}{\sin\theta_j}$ from 0 to π (b) $\frac{\theta_j - 2\pi}{\sin\theta_j}$ from π to 2π

Fig. 4

Guidance law proposed in eqn. (5) takes care of the fact that if pursuer i has less impact time than $i+1$, then pursuer i goes along the straight line path, eventually increasing its impact time $\tilde{t}_i$, till it becomes equal to $\tilde{t}_{i+1}$. After this, both of them can go along respective circular paths. Thus, ensuring that both the pursuers reach the target simultaneously. Circular trajectories are chosen to reach the target as they require constant lateral acceleration as an input.

***Property** 2:* Consider a pursuer j, $j \in \{1,..,n\}$, with kinematics given by eqn. (1). If the pursuer j keeps moving on a fixed circular trajectory to intercept the target, its desired impact time $\tilde{t}_j$ decreases.

The proof is omitted as it is too obvious.

As stated just after eqn. (5), now we explain how guidance law proposed in eqn. (5) helps us in achieving simultaneous target interception.

***Theorem** 1:* The system of pursuers with the kinematics given by eqn. (1) in a cyclic communication topology following the guidance law defined in eqn. (5), is guaranteed to achieve simultaneous interception from any arbitrary initial conditions.

Proof: At the start of the pursuit, say pursuer i, has the largest value of $\tilde{t}$ where $i \in \{1,2,...,n\}$. According to eqn. (5), this implies $a_i = a_i'$, and by Property 2, $\tilde{t}_i$ decreases. Similarly as per eqn. (5) and Property 1, $\tilde{t}_{i-1}$ increases, leading $\tilde{t}_i$ to decrease and $\tilde{t}_{i-1}$ to increase, regardless of changes in other $\tilde{t}$ values. This process continues until $\tilde{t}_i$ and $\tilde{t}_{i-1}$ are equal. Since, $\tilde{t}_i$ was greatest in the beginning so now both $\tilde{t}_i$ and $\tilde{t}_{i-1}$ will be largest.

Next, by eqn. (5), $a_{i-1} = a_{i-1}'$. At this point, with $\tilde{t}_i$ and $\tilde{t}_{i-1}$ equal and maximal, they both decrease, while $\tilde{t}_{i-2}$ increases(due to (5) and Property 1) until it matches $\tilde{t}_i$ and $\tilde{t}_{i-1}$. Consequently, $\tilde{t}_i$, $\tilde{t}_{i-1}$ and $\tilde{t}_{i-2}$ all become equal.

This pattern continues as pursuer $i-3$ catches up with $i, i-1, i-2$, and so on, until all $\tilde{t}$ values are equal. Hence proved. ■

The proposed guidance law works for all values of θ from $0+\varepsilon$ to $\pi-\varepsilon$ and from $\pi+\varepsilon$ to $2\pi-\varepsilon$. Note that ε is very small for all practical purposes. So, the proposed law can be implemented practically.

In cyclic communication topology, the entire path of the pursuer with the largest $\tilde{t}$ can always be predicted.

***Corollary** 1:* The pursuer with the largest value of $\tilde{t}$ at time $t = 0$, always moves in a circle of fixed radius.

Proof: It is evident from eqn. (5), any pursuer i with largest $\tilde{t}_i$ will always have $a_i = a_i{}'$ as provided in eqn. (4), which insinuates circular path of fixed radius. ■

Similarly, the time of impact of the pursuer with the largest value of $\tilde{t}$ can also be predicted, which in turn dictates the impact time of the entire system.

***Corollary** 2:* The simultaneous time of impact of all the pursuers is equal to the impact time of the pursuer with the largest value of $\tilde{t}$ at time $t = 0$.

Proof: Eqn. (5) under cyclic communication guarantees that all pursuers intercept the target simultaneously. As stated in Corollary 1, the pursuer with the largest value of $\tilde{t}$ always moves along a circle of fixed radius. Since all other pursuers have smaller $\tilde{t}$ values, they synchronise their $\tilde{t}$ values with the largest $\tilde{t}$, as shown in Theorem 1. Thus, the interception time becomes $(arc\ length)/(speed)$, where both numerator

and denominator are fixed for any given initial condition. Hence, proved. ■

Although the entire path of all the pursuers can not be predicted, it can be done for some time period of the pursuit.

***Corollary** 3:* All the pursuers follow circular trajectories after some finite time(say t_β), where t_beta is always less than the final time of interception.

Proof: Eqn. (5) is designed to equalise all $\tilde{t}$ values before interception, which is necessary for simultaneous interception. Once their $\tilde{t}$ values become equal(let's denote this moment as t_β), then the eqn. (5b) directs them to follow circular paths to intercept the target. This behaviour is also confirmed by simulation results later in the paper. ■

It is clear that the entire path of all the pursuers cannot be predicted in cyclic communication topology, but if it were to be predicted, then the communication topology should be all-to-all.

***Corollary** 4:* If all-to-all communication were to be allowed, then the path of each pursuer can exactly be predicted by slightly modifying the guidance law. The pursuer with the largest $\tilde{t}$ value moves on a circle of fixed radius throughout, while all the other pursuers take a straight line segment which is then followed by a circular arc.

Proof: The modified guidance law then becomes

$$a_i = \begin{cases} 0 & \text{if } \tilde{t}_i < \tilde{t}_j; \quad j \in \{1,2,...,n\} \setminus \{i\} \\ a_i' & \text{if } \tilde{t}_i \geq \tilde{t}_j; \quad j \in \{1,2,...,n\} \end{cases} \tag{8}$$

The pursuer with the largest $\tilde{t}$ value follows a circular path, which follows from Corollary 1. All the other pursuers first take a straight line segment and then a circular path, which follows from eqn. (8) and can be proved easily by imitating the proof of Theorem 1. ■

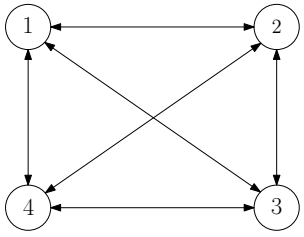


Fig. 5: An example of all-to-all Communication Topology

Similarly, the guidance law can also be modified for bicycle communication topology.

***Corollary** 5:* For bicycle communication, as shown in Fig. 6, to achieve simultaneous interception from any arbitrary initial condition, the guidance law should be

$$a_i = \begin{cases} 0 & \text{if } \tilde{t}_i < \tilde{t}_j; \quad j \in \{i-1, i+1\} \\ a_i' & \text{if } \tilde{t}_i \geq \tilde{t}_j; \quad j \in \{i-1, i+1\} \end{cases} \tag{9}$$

Proof: The proof follows from Theorem 1. ■

Let a_m be the bound on lateral acceleration that one would like to impose on the system. Then, to achieve this bound,

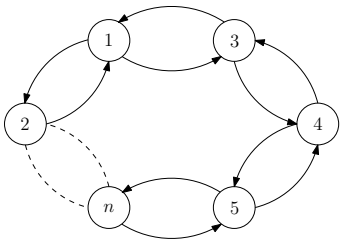


Fig. 6: Bicycle Communication Topology

(5) again needs to be modified slightly, which then becomes,

$$a_i = \begin{cases} (-sgn(\sin\theta_i))a_m & \text{if } \tilde{t}_i < \tilde{t}_{i+1} \ \& \ |\theta_i| < \arcsin\frac{2V_i^2}{a_m R_i} \\ 0 & \text{if } \tilde{t}_i < \tilde{t}_{i+1} \ \& \ |\theta_i| > \arcsin\frac{2V_i^2}{a_m R_i} \\ (-sgn(\sin\theta_i))a_m & \text{if } \tilde{t}_i \geq \tilde{t}_{i+1} \ \& \ |a_i'| > a_m \\ a_i' & \text{if } \tilde{t}_i \geq \tilde{t}_{i+1} \ \& \ |a_i'| \leq a_m \end{cases} \tag{10}$$

Here, $sgn()$ represents the signum function. While we still need to get a formal proof of eqn. (10), we can confidently assert that a_m has a lower bound. This is because all pursuers must first synchronise their $\tilde{t}$ values and then follow circular paths once these values become equal, which requires some non-zero finite lateral acceleration to maintain the circular trajectories. This is only possible if a_m has a lower bound. Additionally, the time of interception decreases as a_m increases, since no lower bound on a_m implies the fastest possible time of interception, making eqn. (10) equivalent to eqn. (5)). However, When eqn. (10) is used as the guidance law instead of eqn. (5), Corollaries 1,2 and 4 no longer hold. Corollary 3 does remain valid though.

The desired impact time has a lower bound due to practical limitations like speed limitations, actuator saturation, and constraints on pursuers' initial conditions. Therefore, any impact time greater than this limit is feasible. From Corollary 2, the simultaneous impact time is determined by the pursuer with the largest $\tilde{t}$ value at $t = 0$. By controlling this pursuer's impact time, we can control the interception time for all the pursuers. To adjust the impact time for the pursuer with the largest $\tilde{t}$, we need to modify θ in the eqn. (3) accordingly and the other pursuers will follow as described in Theorem 1, resulting in desired simultaneous interception time.

Numerical simulations have been carried out to illustrate the theoretical results, which are discussed in the next section.

IV. Simulation Results

The numerical simulations of the proposed law are shown in this section. Other theoretical results can also be verified. The target is stationary and is located at the origin.

Case 1:

The number of pursuers is 4. Linear speeds are V=[60 70 80 90], initial values of lead angles are θ=[245 −65 25 35]. Starting positions are

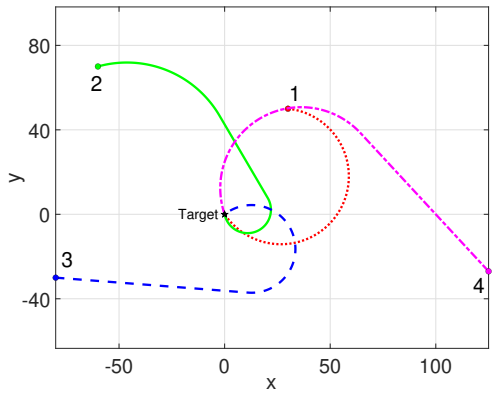


Fig. 7: Trajectories of pursuers for cyclic communication(Case 1)

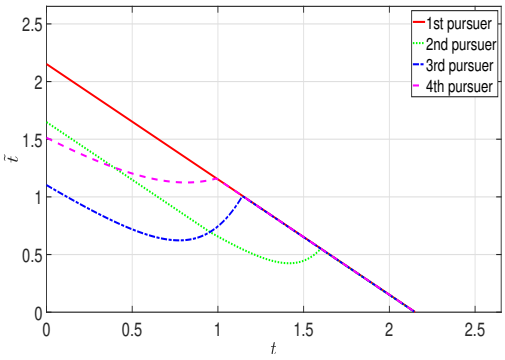


Fig. 8: $\tilde{t}$ vs t for cyclic communication(Case 1)

$(30,50),(-60,70),(-80,-30),(125,-27)$ respectively. The communication topology used in this case is cyclic. Fig.7 shows the trajectories of all the pursuers finishing at the same point, and Fig.8 shows the impact time of all the pursuers versus time, which confirms that the impact is simultaneous.

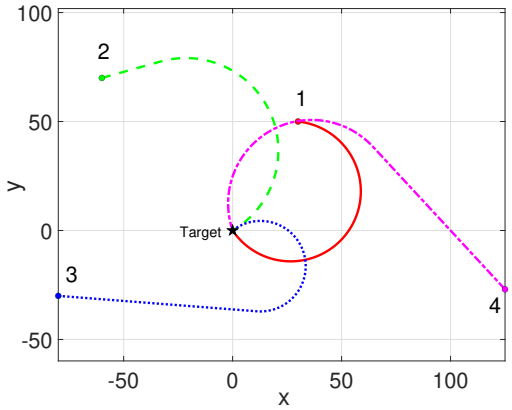


Fig. 11: Trajectories of pursuers for bicyclic communication(Case 3)

Case 2:

The number of pursuers is 4. The linear speeds of pursuers are V=[40 35 45 38], initial values of lead angles are θ=[45 65 25 135]. The communication topology used in this case is all-to-all. Starting positions of pursuers are $(80,10),(-60,80),(-80,-300),(125,-127)$ respectively. Fig. 9 shows the trajectories of pursuers, and curves in Fig.10 denote the impact time of all the pursuers versus time. Both Fig. 9 and Fig.10 confirm the simultaneous interception of the target.

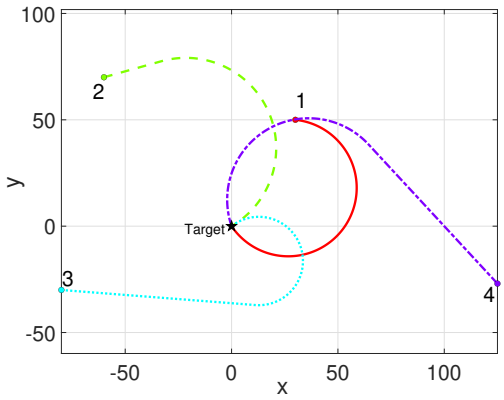


Fig. 9: Trajectories of pursuers for all-to-all communication(Case 2)

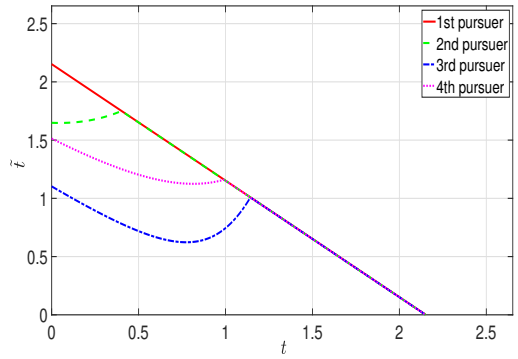


Fig. 10: $\tilde{t}$ vs t for all-to-all communication(Case 2)

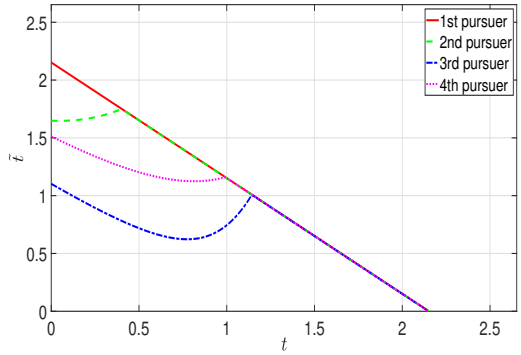


Fig. 12: $\tilde{t}$ vs t for bicyclic communication(Case 3)

Case 3:

The number of pursuers is 4. The linear speeds of pursuers are V=[40 35 45 38], initial values of lead angles are θ=[45 65 25 135]. The communication topology

used in this case is bicycle communication(an example of which is shown in Fig. 6). Starting positions of pursuers are $(80,10),(-60,80),(-80,-300),(125,-127)$ respectively. Fig. 11 shows the trajectories of pursuers, and curves in Fig.10 denote the impact time of all the pursuers versus time. Both Fig. 11 and Fig.12 confirm the simultaneous interception of the target.

V. CONCLUSION

This paper introduces a distributed guidance law for a system of heterogeneous autonomous pursuers, applicable to any arbitrary initial positions and heading angles. We propose using straight lines and circles due to their simplicity in design and implementation. While we employ cyclic communication topology in this study for the reasons outlined in Section I, this law can be adapted to other communication topologies with some modifications, one of which is discussed in Corollary 4. We also derived the necessary conditions to impose the desired time of impact. Simulation results are provided to validate the claims, demonstrating that all $\tilde{t}$ values converge to zero simultaneously in each case. Future work could be an extension of this approach to manoeuvring target.

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