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Differential game with slow pursuers on the 1-skeleton graph of the dodecahedron

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Abstract. This work is devoted to study pursuit problems involving multiple pursuers and a single evader, all moving on the 1-skeleton graph of the dodecahedron. Solutions to the pursuit problems are provided, where the maximum speeds of the pursuers are less than the maximum speed of the evader. Conditions for the maximum speeds of the pursuers are obtained and a strategy for the pursuers to capture the evader is presented.

Keywords: Differential game, pursuers, evader, pursuit problem, 1-skeleton graph of the dodecahedron, slow evaders, number of pursuers
MSC (2020): 05C57; 91A43

1. Introduction

According to the fundamental principles of differential games developed by N.N. Krasovskii, L.S. Pontryagin, A.I. Subbotin, and others, a differential game is considered as a control problem from the perspective of either the pursuer or the evader [1, 2, 3, 4]. From this viewpoint, the game reduces either to a pursuit problem (pursuit) or to an evasion problem (evasion) [5, 6, 7, 8, 9, 10, 11].

Multi-pursuer differential games are of increasing interest (see, for example, [12, 13, 9, 14, 15, 16, 14, 17, 18, 19]).

There are several types of dynamic games on graphs. The first and most studied type is the class of games on abstract graphs. Using such games, well-known mathematicians such as M. Aigner, T. Andreae, A. Bonato, R.J. Nowakowski, M. Fromme, A. Quilliot and others have conducted research and obtained significant results [20, 21, 13, 22, 6, 23, 24, 9, 25]. A relatively narrower, but more interesting class of dynamic games on geometric graphs involves the classical "pursuer-evader" game with moving points moving along the edges of the graph. Dynamic games of this type have been studied by A.A. Azamov, A.Sh. Kuchkarov, G. Ibragimov, T. Ibaydullaev, and A.G. Holboyev, yielding interesting results [21, 14, 17, 18, 19, 26].

When considering a pursuit problem, we assume that the evader Q is initially located on an arbitrary edge of the dodecahedron, and we control the pursuers with the aim of capturing the evader. Therefore, we place the pursuers on the edges of the dodecahedron according to our objective and maneuver them based on a strategy aligned with this goal. The strategy of the evader is assumed to be arbitrary. On the other hand, when considering an evasion problem, we assume that initial positions of the pursuers P_i, $i = 1, 2, \dots, m$, are arbitrary, and we control the evader with the aim of avoiding encounters with the pursuers. Therefore, we position the evader on the edges of the dodecahedron according to our objective and maneuver it based on a strategy corresponding to this goal. The strategies of the pursuers are assumed to be arbitrary.

1.1. Statement of problem.

Let

$$AA_1A_2A_3A_{11}A_{12}A_{21}A_{22}A_{31}A_{32}BB_1B_2B_3B_{11}B_{12}B_{21}B_{22}B_{31}B_{32}$$

be a dodecahedron with edges of unit length. We consider that a group of pursuers $\mathbf{P} = \{P_1, P_2, ..., P_m\}$ pursues a single evader Q (Fig.1) along these edges. These are typically called players. We assume that the players always see each other. We use the symbols P_i and Q to denote players and their positions on the edges of the dodecahedron. Naturally, the points P_i and Q are moving points that depend on time: $P_i = P_i(t), Q = Q(t)$. The states of the players at time $t = 0$ are called initial states or initial positions of the players. Clearly, these are given by $P_i(0)$, $Q(0)$, $i = 1, 2, ..., m$.

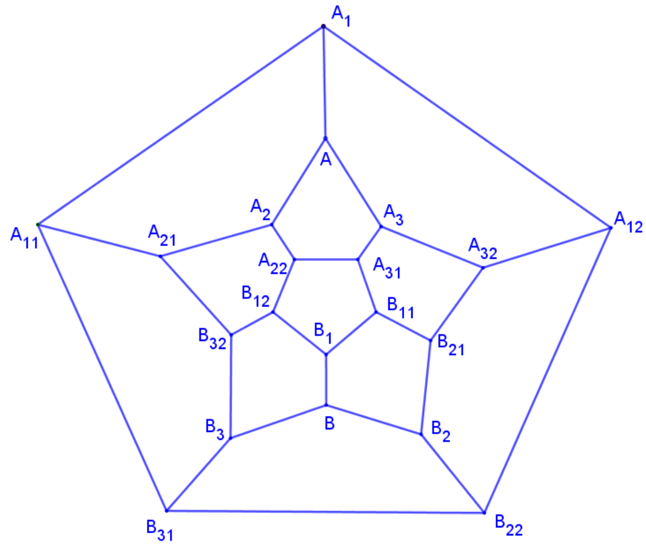

Figure 1. 1-skeleton graph of a dodecahedron.

Definition 1.1. If there exists a strategy for the group of pursuers $\mathbf{P} = \{P_1, P_2, ..., P_m\}$ such that, under this strategy, there is a time $T > 0$ for which, regardless of the evader's strategy and initial position on any edge of the dodecahedron, the equality $P_i(T) = Q(T)$ holds for some $i = 1, 2, ..., m$, then the pursuers are said to win the game (or equivalently, the game can be concluded in favor of the pursuers in finite time, or simply, the game is completed).

Here, T is called the guaranteed pursuit time.

Suppose that the players move simply along edges of the dodecahedron. Let the velocity vector of the evader be denoted by v and its maximum magnitude be denoted by σ. Likewise, let those of the pursuers be denoted by u_i and their respective maximum magnitudes by ρ_i: $|v| \le \sigma$, $|u_i| \le \rho_i$, $\sigma \ge \rho_1 \ge \rho_2 \ge ... \ge \rho_m > 0$.

2. Main result

According to the above, the motions of the players are given by

$$\dot{P}_i(t) = u_i, P_i(0) = P_{i0}, i = 1, 2, ..., m;$$

$$\dot{Q}(t) = v, Q(0) = Q_0.$$

Actually, $P_i, Q, u_i, v \in \mathbb{R}^3$, but since the game is considered on a graph, we can assume that $P_i, Q, u_i, v \in \mathbb{R}^2$.

Theorem 2.1. *If $\sigma = 1, \rho_1 = \frac{2}{3}, \rho_2 = \frac{2}{3}$ and $\rho_3 > 0$, then the group of pursuers $\boldsymbol{P} = \{P_1, P_2, P_3\}$ wins the game.*

Proof. Let the game begin from an arbitrary initial position. Since we control the pursuers, within some time moment $t = t_1$, we can move pursuer P_1 to vertex A, pursuer P_2 to vertex B and during this time interval, the third pursuer P_3 continuously pursues the evader Q (see Fig. 2a).

At this time, the evader Q is located at some vertex or edge of the dodecahedron.

Lemma 2.2. *Pursuer P_1 can guard the edges AA_1, AA_2, AA_3, emanating from vertex A.*

Proof. The pursuer P_1 and the evader Q can be in one of the following three states:

$$a)|AQ| > 2.5, \quad b)|AQ| = 2.5, \quad c)|AQ| < 2.5.$$

In each case, we will show how the pursuer P_1 moves and how it guards the edges AA_1, AA_2, AA_3. a) Let $|AQ| > 2.5$. The pursuer P_1 remains without moving at vertex A until the evader Q approaches within distance $|P_1Q| = 2.5$. If the evader Q reaches distance $|P_1Q| = 2.5$, then we continue with the case b).

b) Let $|AQ| = 2.5$. In this case, the evader Q is located at the midpoint of one of the following edges: $A_{11}B_{31}, A_{11}A_{21}, A_{21}B_{32}, A_{22}B_{12}, A_{22}A_{31}, A_{31}B_{11}, A_{32}B_{21}, A_{32}A_{12}, A_{12}B_{22}$ (Fig. 2b). □

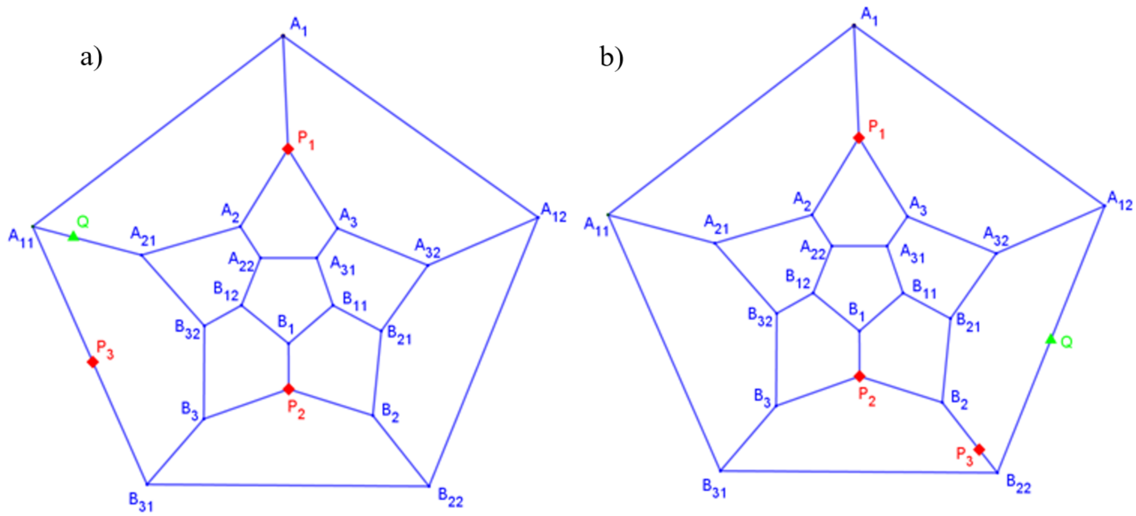

Figure 2. a) a case when $|AQ| > 2.5$; b) a case when $|AQ| = 2.5$.

If the evader Q moves toward a vertex B_{ij}, then the pursuer P_1 remains stationary at vertex A (we return to case a)).

If the evader Q moves toward a vertex A_{ij}, then the pursuer P_1 moves along the edge AA_i, maintaining the relation $3P_1A = 1 - 2QA_{ij}$ with the evader Q. When the evader Q reaches the vertex A_{ij}, the pursuer P_1 reaches a point located at $\frac{1}{3}$ of the edge AA_i from vertex A (see Fig. 3a).

Next, if the evader Q continues moving toward the vertex A_i, then the pursuer P_1 also moves along the edge AA_i toward the vertex A_i, maintaining the relation $3P_1A_i = 2QA_i$ with the evader Q. If the evader Q reaches the vertex A_i, then the pursuer P_1 simultaneously reaches the same vertex and captures the evader Q. If the evader Q chooses to move along a different edge without proceeding from A_{ij} to A_i, then the pursuer P_1 moves back toward vertex A. When the evader Q reaches the midpoint of an edge, the pursuer P_1 returns to vertex A, returning to the case b), where $|P_1Q| = 2.5$. Using the above strategy, the pursuer P_1 can guard edges AA_1, AA_2, AA_3.

c) Suppose that $|AQ| < 2.5$. In this case, the evader Q moves along the path $AA_iA_{ij}C$, i.e., along the broken line $AA_iA_{ij}C$. Here, the point C is the midpoint of an edge which is formed from vertex A_{ij} and satisfying the condition $|AC| = 2.5$ (Fig. 3b).

The pursuer P_1 moves toward the evader Q along the broken path $AA_iA_{ij}C$ until the relation $|QC| = 1.5|AP_1|$ is satisfied. As a result, the pursuer will either capture the evader Q or the condition $|QC| = 1.5|AP_1|$ will be satisfied (see Fig. 4a). Once the relation $|QC| = 1.5|AP_1|$ holds, the pursuer P_1 continues moving symmetrically with respect to the evader Q, just as in case b). Using this strategy, the pursuer P_1 maintains control over the edges AA_1, AA_2, AA_3.

Thus, it has been shown that the pursuer P_1 can guard the edges AA_1, AA_2, AA_3 emanating from from vertex A. Lemma 2.2 is proved.

According to the lemma 2.2, the pursuer P_2 can similarly guard the edges BB_1, BB_2, BB_3 emanating from vertex B.

The pursuer P_3 always pursues the evader Q. Due to the pursuit by P_3, the evader Q will be forced to move sequentially through the vertices of the dodecahedron. Assume that at time $t = t_2$, where $t_2 \geq t_1$, the evader Q is located at a vertex A_{ij} or B_{ij} of the dodecahedron. If the evader Q moves from vertex A_{ij} or B_{ij} to vertex A_i or B_i, respectively, then according to Lemma 2.2, the pursuer P_1 or P_2 will intercept and capture the evader accordingly. To avoid being captured by P_1 or P_2, the evader Q must move only through the vertices A_{ij} and B_{ij}. The path connecting these vertices consists of a single cycle: $A_{11}A_{21}B_{32}B_{12}A_{22}A_{31}B_{11}B_{21}A_{32}A_{12}B_{22}B_{31}A_{11}$ (Fig. 4.b)

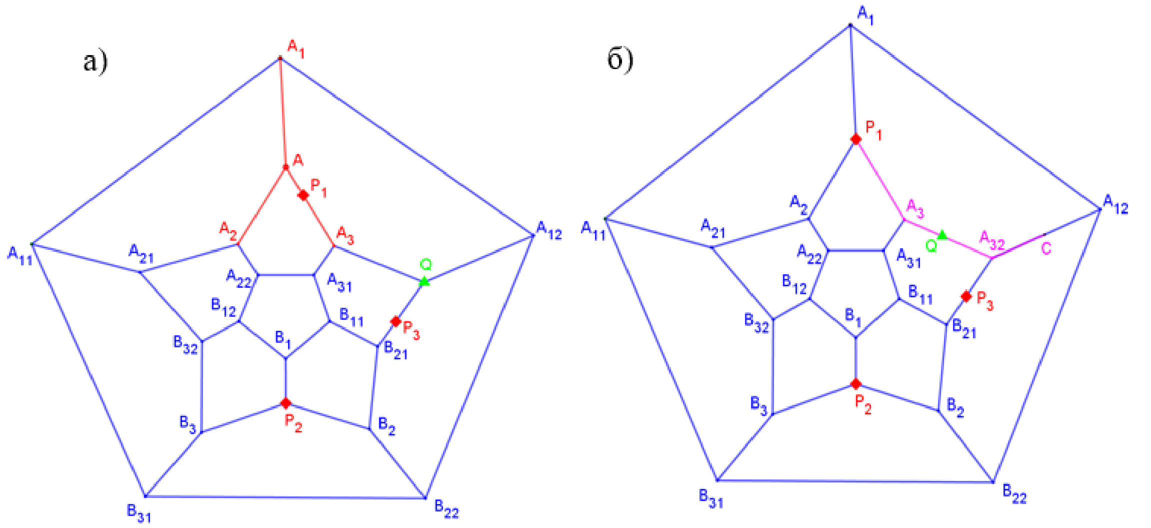

Figure 3. a) guarding the edges AA_1, AA_2, AA_3 by the pursuer P_1; b) a case when $|AQ| < 2.5$.

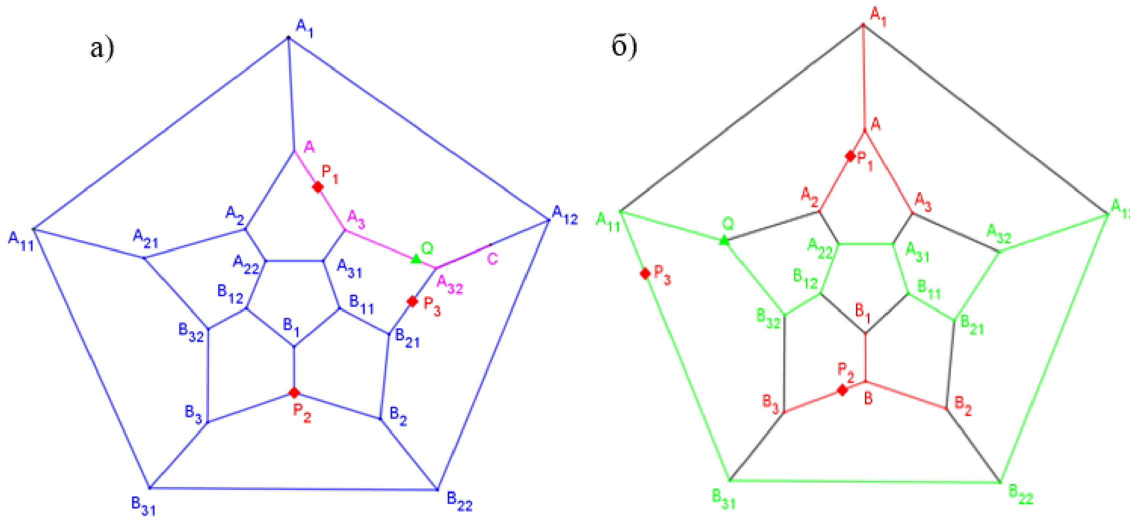

Figure 4. a) the condition $|QC| = 1.5|AP_1|$ will be satisfied; b) the cycle $A_{11}A_{21}B_{32}B_{12}A_{22}A_{31}B_{11}B_{21}A_{32}A_{12}B_{22}B_{31}A_{11}$.

The pursuer P_3 can pursue the evader Q either clockwise or counterclockwise along the cycle

$$A_{11} \to A_{21} \to B_{32} \to B_{12} \to A_{22} \to A_{31} \to B_{11} \to B_{21} \to A_{32} \to A_{12} \to B_{22} \to B_{31} \to A_{11}.$$

Suppose that the pursuer P_3 pursues the evader Q in the clockwise direction.

Let, at time $t = t_3$, where $t_3 \geq t_2$, the evader Q moves to the vertex B_{31} of the dodecahedron. At this moment, the pursuer P_1 is located at a point $\frac{1}{3}$ along the edge AA_1 from vertex A, while the pursuer P_2 is located at a point $\frac{1}{3}$ along the edge BB_3 from vertex B, and the pursuer P_3 is pursuing the evader Q (see Fig. 5a).

Starting from time $t > t_3$, the pursuers will move as follows:

The pursuer P_3 continues to pursue the evader Q along the cycle

$$A_{11} \to A_{21} \to B_{32} \to B_{12} \to A_{22} \to A_{31} \to B_{11} \to B_{21} \to A_{32} \to A_{12} \to B_{22} \to B_{31} \to A_{11}.$$

As a result, the evader Q should move from the vertex B_{31} to an adjacent vertex of the dodecahedron, otherwise the pursuer will catch the evader.

If the evader Q moves along the edge $B_{31}B_{22}$ toward the vertex B_{22}, then it will be captured by pursuer P_3.

If the evader Q moves toward the vertex B_3 along the edge $B_{31}B_3$, then according to the lemma, it will be captured by the pursuer P_2.

If the evader Q moves along the edge $B_{31}A_{11}$ toward the vertex A_{11}, then the pursuer P_1 follows the strategy described in Lemma 2.2, while the pursuer P_2 moves along the edge BB_3 toward the vertex B_3, maintaining the relation $3|P_2B_3| = 2|QA_{11}|$ with the evader Q. At time $t = t_4$, where $t_4 > t_3$, the evader Q reaches the vertex A_{11} of the dodecahedron, the pursuer P_1 is located at a point $\frac{1}{3}$ along the edge AA_1 from vertex A, and the pursuer P_2 is located at vertex B_3 (see Fig. 5b).

The pursuer P_3 continues to pursue the evader Q. The evader Q will again be forced to move to another vertex of the dodecahedron.

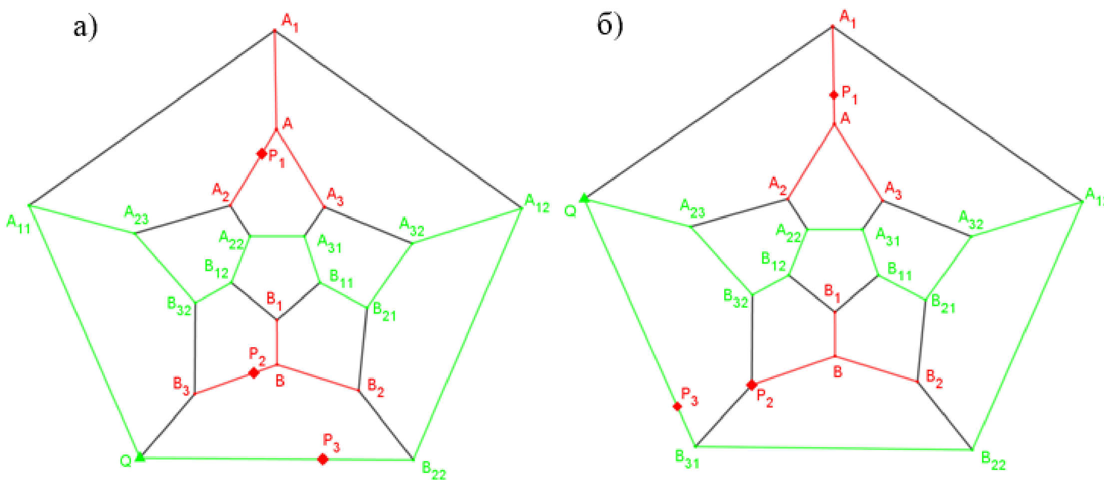

Figure 5. The process of trapping the evader.

If the evader Q moves along the edge $A_{11}B_{31}$ toward the vertex B_{31}, then it will be captured by the pursuer P_3.

If the evader Q moves toward the vertex A_1 along the edge $A_{11}A_1$, then according to the lemma 2.2, it will be captured by the pursuer P_1.

If the evader Q moves toward the vertex A_{21} along the edge $A_{11}A_{21}$, then the pursuer P_1 moves to a point $\frac{1}{3}$ along the edge AA_2 from vertex A, while the pursuer P_2 moves along the edge B_3B_{32} to a point $\frac{2}{3}$ along the edge B_3B_{32} from vertex B_3, maintaining the relation $3|P_2B_{32}| = 1 + 2|QA_{21}|$ with the evader Q. Then, at time $t = t_5$, where $t_5 > t_4$, the evader Q reaches the vertex A_{21} of the dodecahedron, the pursuer P_1 is located at a point $\frac{1}{3}$ along the edge AA_2 from vertex A, and the pursuer P_2 is located at a point $\frac{2}{3}$ along the edge B_3B_{32} from vertex B_3 (see Fig. 6).

At the next step, the evader Q will be captured by the pursuer P_3, if it moves from vertex A_{21} to the adjacent vertex A_{11}, the pursuer P_1, if it moves from vertex A_{21} to the adjacent vertex A_2, the pursuer P_2, if it moves from vertex A_{21} to the adjacent vertex B_{32}.

Theorem 2.1 is proved. □

Theorem 2.3. *If* $\sigma = 1$, $\rho_1 = \frac{1}{3}$, $\rho_2 = \frac{1}{3}$, $\rho_3 = \frac{1}{3}$, *and* $\rho_4 > 0$, *then the group of pursuers* $P = \{P_1, P_2, P_3, P_4\}$ *wins the game.*

Proof. To prove the theorem, it suffices to construct a strategy for the pursuers such that $P_i(T) = Q(T), i = 1, 2, 3, 4$, holds in finite time $T > 0$, starting from an arbitrary initial position.

Since we control the pursuers, within some time $t = t_1$, we can move the pursuer P_1 to a point $\frac{1}{3}$ along the edge AA_1, measured from vertex A, the pursuer P_2 to a point $\frac{1}{3}$ along the edge B_2B_{21},

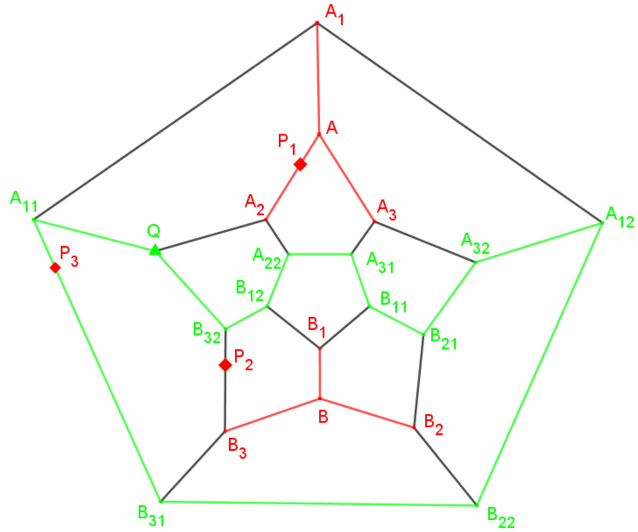

Figure 6. Critical moment in the pursuit with Q trapped between P_1, P_2 and P_3, ensuring eventual capture.

measured from vertex B_{21}, the pursuer P_3 to a point $\frac{1}{3}$ along the edge B_3B_{32}, measured from vertex B_{32}, while the fourth pursuer P_4 continuously pursues the evader Q during this time interval (see Fig. 7a).

From this moment on, the pursuers P_1, P_2, P_3 guard the edges $AA_1, B_2B_{21}, B_3B_{32}$, respectively, where they are positioned.

Lemma 2.4. *The pursuer P_1 can guard the edge AA_1.*

Proof. Let at time $t = t_1$, the pursuer P_1 be located at a point $\frac{1}{3}$ along the edge AA_1, measured from vertex A (see Fig. 7a). As a result of the pursuit by P_4, the evader Q is forced to move through the vertices of the dodecahedron; otherwise, it will be captured by P_4. We now show how the pursuer P_1 moves depending on the motion of the evader Q, such that P_1 maintains control over the edge AA_1.

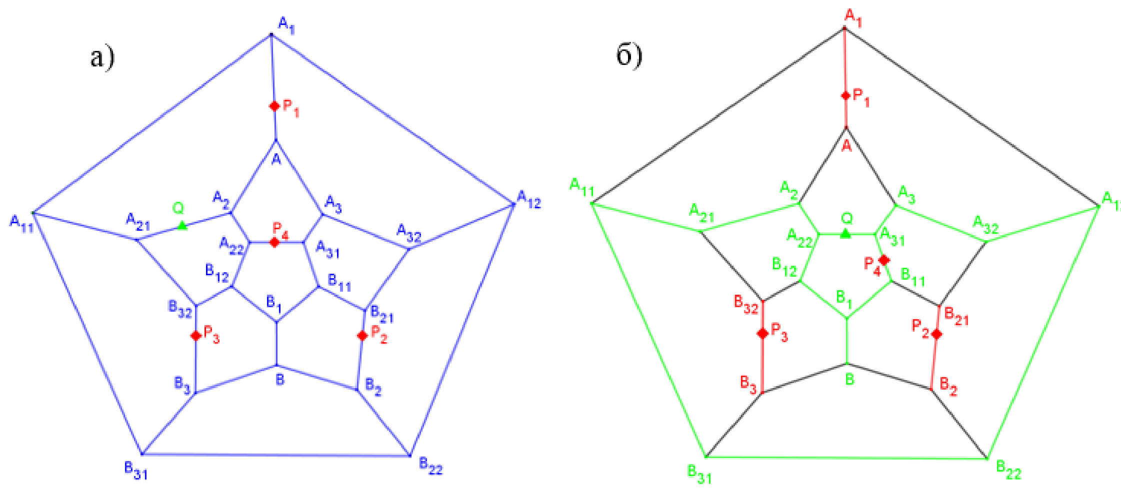

Figure 7. Guarding edges by P_1, P_2, P_3 pursuers.

I. If the evader Q moves from vertex A_2 or A_3 toward vertex A, then the pursuer P_1 also moves toward the same vertex A, maintaining the relation $3|P_1A| = |QA|$ with the evader Q. As a result, if the evader Q reaches vertex A, it will be captured by the pursuer P_1.

II. If the evader Q moves from some vertex toward vertex A_{11} or A_{12}, then the pursuer P_1 moves from the point $\frac{1}{3}$ along the edge AA_1 (measured from vertex A) toward the point $\frac{2}{3}$ along the same edge AA_1. If the evader Q reaches vertex A_{11} or A_{12}, then the pursuer P_1 reaches the point $\frac{2}{3}$ along the edge AA_1, measured from vertex A.

III. If the evader Q moves from some vertex toward vertex A_2 or A_3, then the pursuer P_1 moves from the point $\frac{2}{3}$ along the edge AA_1 (measured from vertex A) back toward the point $\frac{1}{3}$ along the same edge AA_1. If the evader Q reaches vertex A_2 or A_3, then the pursuer P_1 reaches the point $\frac{1}{3}$ along the edge AA_1, measured from vertex A.

IV. If the evader Q moves from vertex A_{11} or A_{12} toward vertex A_1, then the pursuer P_1 also moves toward the same vertex A_1, staying on the same line as the evader Q. As a result, the evader Q will be captured by the pursuer P_1 at vertex A_1.

V. In all other cases, the pursuer P_1 remains stationary.

Thus, it has been shown that if the evader Q reaches either vertex A or A_1 of the edge AA_1, it will be captured by the pursuer P_1 using the strategy described above.

Therefore, the pursuer P_1 can guard the edge AA_1. The edges AA_1, AA_2, AA_3, A_1A_{11}, A_1A_{12}, which share the vertices A and A_1, are highlighted with red lines (see Fig. 7b). □

Applying Lemma 2.4 to the pursuers P_2 and P_3, it can be shown that they can also take control of the edges B_2B_{21}, B_3B_{32} and adjacent edges (highlighted with red lines, see Fig. 7b).

The pursuer P_4 always pursues the evader Q. In order for evasion to occur, the evader Q must not be captured by any of the pursuers within an infinite time interval. As a result of the pursuit by P_4 and the application of Lemma 2.4 to the pursuers P_1, P_2, P_3, the evader Q is forced to move along the green-colored edges of the dodecahedron (see Fig. 7b). The part of the dodecahedron formed by the green edges consists of three cycles. Due to the pursuit by P_4, the evader Q may move either clockwise or counterclockwise along these cycles.

Assume that at time $t = t_2$, where $t_2 \geq t_1$, the evader Q is located at vertex A_{22} of the dodecahedron and the pursuer P_4 is pursuing along the edge $A_{22}A_{31}$ (see Fig. 8a).

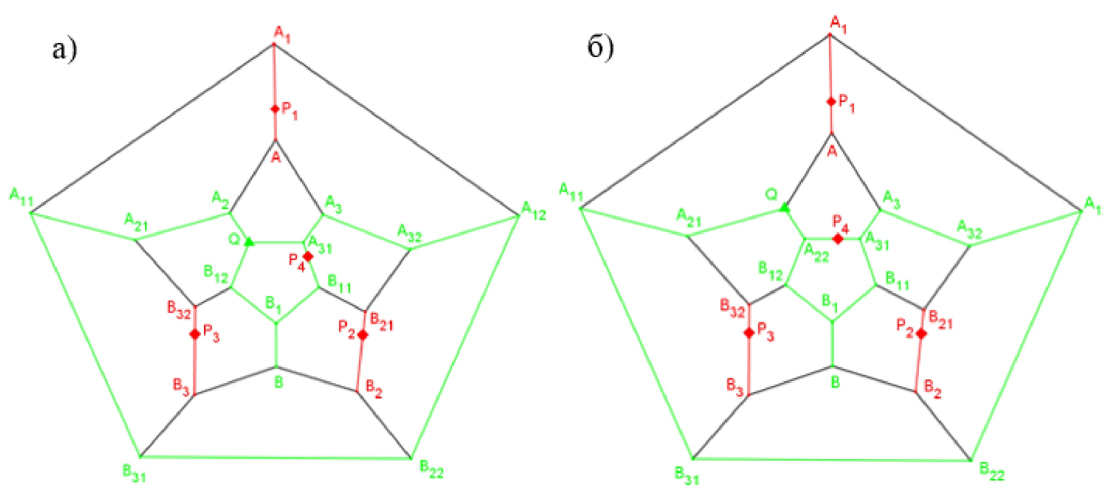

Figure 8. Cycles that the evader Q can move.

Starting from this moment, the evader Q can move along one of two cycles, since other cycles are guarded by the pursuers:

a) in the direction $A_{22} \to A_2 \to A_{21} \to A_{11} \to \ldots$;

b) in the direction $A_{22} \to B_{12} \to B_1 \to B_{11} \to \ldots$.

We will consider these two directions separately.

First, consider the case where the evader Q moves in the direction $A_{22} \to A_2 \to A_{21} \to A_{11} \to \ldots$.

Suppose that starting at time $t = t_2$, the evader Q begins to move toward vertex A_2 along the path $A_{22} \to A_2 \to A_{21} \to A_{11} \to \ldots$ and reaches A_2 at time $t = t_3$, where $t_3 \geq t_2$. At this moment, the pursuer P_1 is located at a point $\frac{1}{3}$ along the edge AA_1, measured from vertex A (see Fig. 8b).

Next, suppose that starting at time $t = t_3$, the evader Q moves toward vertex A_{21} along the edge A_2A_{21} and reaches it at time $t = t_4$, where $t_4 \geq t_3$. At this moment, the pursuer P_1 is located at a point $\frac{2}{3}$ along the edge AA_1, measured from vertex A and the pursuer P_3 is located at a point $\frac{1}{3}$ along the edge B_3B_{32}, measured from vertex B_{32} (see Fig. 9a).

In the same way, the pursuer P_4 continues to pursue the evader Q. If the evader Q moves from vertex A_{21} to vertex A_{11}, then the pursuer P_1 moves toward vertex A_1. As a result, when the evader Q arrives at vertex A_{11} at time $t = t_5$, where $t_5 \geq t_4$, the pursuer P_1 also arrives at vertex A_1 at the same time (see Fig. 9b).

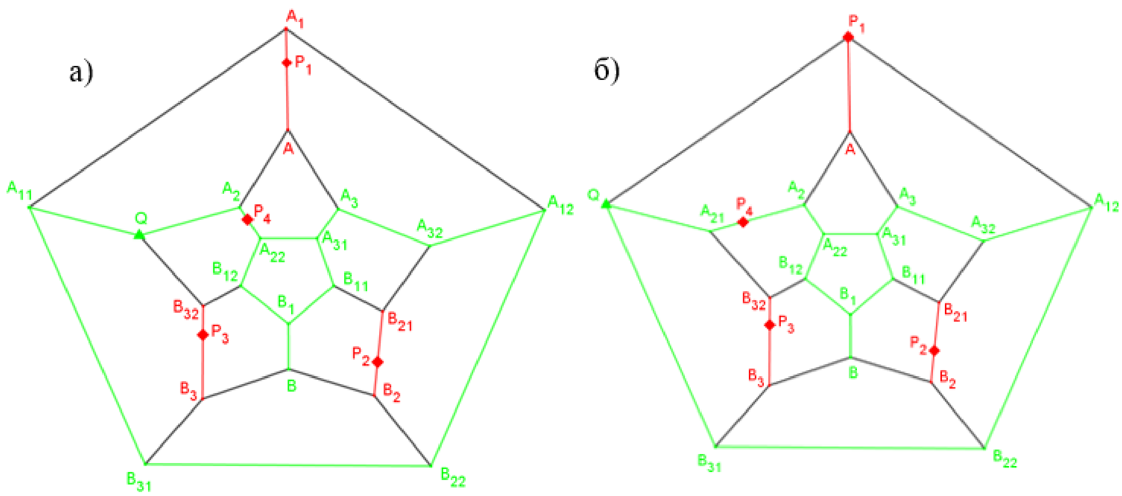

Figure 9. The process of trapping the evader.

If the evader Q moves from vertex A_{11} to vertex B_{31}, then the pursuer P_1 moves along the edge A_1A_{12} and the pursuer P_3 moves along the edge $B_{32}B_3$. If the evader Q reaches vertex B_{31} at time $t = t_6$, where $t_6 \geq t_5$, then the pursuer P_1 will be located at a point $\frac{1}{3}$ along the edge A_1A_{12}, measured from vertex A_1 and the pursuer P_3 will be located at a point $\frac{2}{3}$ along the edge B_3B_{32}, measured from vertex B_{32}, at that moment (see Fig. 10a).

As a result of the pursuit by P_4, if the evader Q continues its motion from vertex B_{31} to vertex B_{22}, then the pursuer P_1 continues moving along the edge A_1A_{12}. If the evader Q arrives at vertex B_{22} at time $t = t_7$, where $t_7 \geq t_6$, then the pursuer P_1 will be located at a point $\frac{2}{3}$ along the edge A_1A_{12}, measured from vertex A_1 and the pursuer P_2 will be located at a point $\frac{1}{3}$ along the edge $B_{21}B_2$, measured from vertex B_2, at that moment (see Fig. 10b).

Thus, as a result of the pursuit by the pursuers P_1, P_2, P_3 and P_4, the evader Q will be captured at time $t = t_8$, where $t_8 \geq t_7$.

If the evader Q moves in the direction $A_{22} \to B_{12} \to B_1 \to B_{11} \to \ldots$, then the pursuers, by using a strategy similar to the one used in the direction $A_{22} \to A_2 \to A_{21} \to A_{11} \to \ldots$, will also capture the evader.

Theorem 2.3 is proved. □

3. Conclusions

This paper investigates pursuit differential games on the 1-skeleton graph of a dodecahedron, focusing on scenarios where multiple pursuers aim to capture a single evader with higher maximum speed. The study provides rigorous strategies and conditions under which the pursuers can guarantee the capture of the evader in finite time, despite the evader's speed advantage. The result of the paper shows that reducing the speed of the pursuers causes the number of pursuers to increase. Moreover, the findings advance the understanding of differential games on polyhedral graphs and demonstrate how slower pursuers can overcome a faster evader through strategic positioning and collaboration. Future research could explore generalizations to other regular polyhedra, dynamic speed adjustments,

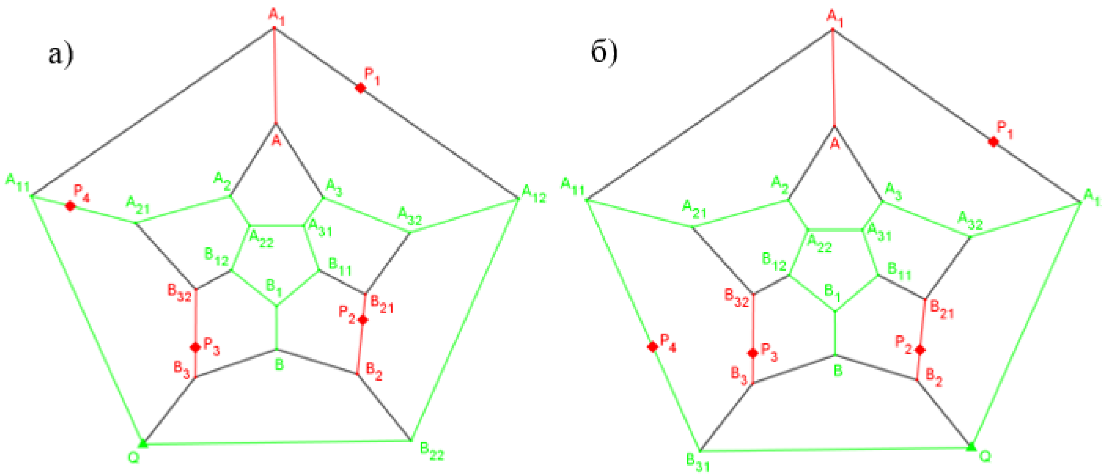

Figure 10. The evader's remaining escape routes are eliminated by pursuers' movements.

or stochastic evader behavior. This work bridges combinatorial game theory and geometric control, offering practical insights for applications in robotics, surveillance, and network security.

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