ՀՀ ԳԱԱ ԻՆՖՈՐՄԱՏԻԿԱՅԻ ԵՎ ԱՎՏՈՄԱՏԱՑՄԱՆ ՊՐՈԲԼԵՄՆԵՐԻ ԻՆՍՏԻՏՈՒՏ

Վահագն Գևորգի Մելքոնյան

Թիրախին հետևող ԱԹՍ ավտոպիլոտի մշակում համակարգչային տեսողության կիրառմամբ

Ե.13.04 - «Հաշվողական մեքենաների, համալիրների, համակարգերի և ցանցերի մաթեմատիկական և ծրագրային ապահովում» մասնագիտությամբ տեխնիկական գիտությունների թեկնածուի գիտական աստիճանի հայցման ատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ - 2025

INSTITUTE FOR INFORMATICS AND AUTOMATION PROBLEMS OF THE NAS RA

Vahagn Gevorg Melkonyan

Development of an UAV autopilot for tracking targets by using computer vision

SYNOPSIS

of the dissertation for obtaining a Ph.D. degree in Technical Sciences on specialty 05.13.04 "Mathematical and Software Support of Computers, Complexes, Systems and Networks"

YEREVAN - 2026

Ատենախոսության թեման հաստատվել է Ռուս-Հայկական (Սլավոնական) Համալսարանում

Գիտական ղեկավար՝ Տեխ.գիտ. դոկտոր Դ.Գ. Ասատրյան

Պաշտոնական ընդիմախոսներ՝ Ֆիզ.մաթ.գիտ. դոկտոր ????????

Տեխ.գիտ. թեկնածու ????????

Առաջատար կազմակերպություն՝ ????????

Պաշտպանությունը կայանալու է ???????? ???????? ՀՀ ԳԱԱ Ինֆորմատիկայի և ավտոմատացման պրոբլեմների ինստիտուտում գործող ???????? մասնագիտական խորհրդում

Ատենախոսությանը կարելի է ծանոթանալ ՀՀ ԳԱԱ ԻԱՊԻ գրադարանում:

Սեղմագիրն առաքված է ????????:

Մասնագիտական խորհրդի գիտական քարտուղար ֆիզ.մաթ.գիտ.դոկտոր՝ Մ.Ե. Հարությունյան

The topic of the dissertation was approved at the Russian-Armenian (Slavonic) University

Scientific supervisor: Doctor of Tech. sciences D.G. Asatryan

Official opponents: Doctor of Phys-Math sciences ????????

Candidate of Tech. sciences ????????

Leading organization: ????????

The defense will take place on ????????, at ???????? (time), at the Institute for Informatics and Automation Problems of the National Academy of Sciences of the Republic of Armenia, at the acting ???????? specialized council.

The dissertation is available in the library of IIAP NAS RA.

The abstract is delivered on ????????.

Scientific Secretary of the Specialized Council, D.Ph.M.S. M.E. Haroutunian

1. Introduction

Over the past two decades, unmanned aerial vehicles (UAVs) have evolved from niche tools in specialized military reconnaissance units into a critical and versatile component of modern technology. Initially, they were primarily tasked with aerial photography, cartography, and intelligence gathering. However, rapid advances in autonomy, computer vision, and onboard processing, combined with the availability of affordable sensors, miniaturized computing platforms, and advanced control algorithms, have enabled UAVs to perform complex operations with minimal human supervision. As a result, UAVs are now widely deployed across civilian, industrial, and defense applications.

UAV-based interception has proven capable of complementing or even replacing traditional manned or ground-based interception systems. They are capable of detecting, tracking, and physically engaging both airborne and ground-based targets without direct human piloting, by reducing response time and operational risk. This technology can also be applied to various tasks, including border and perimeter protection, such as patrolling and intercepting unauthorized ground or aerial intrusions along national borders.

The objective of this work is to design and develop a lightweight, robust, and efficient system for real-time target tracking, interception, and ground control of unmanned aerial vehicles operating in dynamic environments. The system is intended to ensure high reliability, precise guidance, and intuitive operator interaction through a human-machine interface. To achieve this, the **following challenges** must be addressed:

- **Design and develop a lightweight and robust visual tracking module** that delivers stable, real-time performance on onboard hardware under varying environmental conditions and target behaviors, supporting both predefined object classes and class-agnostic tracking to allow dynamic target selection during missions.
- **Design and develop a robust control algorithm for autonomous interception** that accurately guides the UAV toward moving targets while maintaining flight stability and safety, integrating directional estimations, target approach logic, and corrective control adaptable to different target speeds, approach angles, and operational environments.
- **Design and develop a real-time ground control and monitoring system** that features an extended Ground Control Station (GCS) interface, including real-time video streaming, intuitive target selection, in-flight parameter tuning, rapid operator intervention capabilities, and clear visual feedback.

By achieving these objectives, the research aims to develop a UAV interception system that strikes a balance between tracking accuracy, control stability, and user-interface intuitiveness, thereby facilitating the practical deployment of such a system in defense, security, and civilian applications.

The scientific novelty of this work lies in the development of a UAV interception framework that combines lightweight and robust target tracking, precision autonomous control, and real-time ground operator interaction into a single operational system. The contributions of this research extend beyond individual novel algorithms, offering a cohesive architecture suitable for both ground and aerial target interception in real-world conditions.

Key innovative aspects include:

- **A hardware-agnostic framework** that can be deployed on any **multirotor UAV platform** equipped with a compatible flight controller and onboard computer.
- **A real-time hybrid tracking** pipeline designed to run reliably on embedded UAV hardware and to support operator-defined arbitrary targets.
- **Target acquisition algorithm**, which combines deep learning-based object detection with a low-latency tracking mechanism for sustained lock-on.
- **A dual-loop adaptive PID control system** with yaw and pitch guidance, independent roll and thrust control, and real-time in-flight parameter tuning via MAVLink, enabling robust UAV interception.
- **A comprehensive evaluation framework** that integrates Hardware-in-the-Loop (HITL) simulations with diverse target dynamics and real-world field trials conducted under challenging environmental conditions.

From a theoretical standpoint, this research advances the design and implementation principles of autonomous UAV interception systems by proposing a unified ROS 2-based architecture for real-time interception tasks.

The system integrates computer vision modules and operator interaction layers into a single distributed ROS 2 framework, ensuring modularity, scalability, and interoperability with existing UAV platforms. The architecture defines clear data flows between perception, decision-making, and actuation layers, enabling other researchers and developers to adapt or extend the system for related UAV autonomy problems.

From a practical perspective, the results of this work provide a ready-to-use technological foundation for deploying autonomous UAV interception capabilities in real operational environments.

The developed system has been validated in both high-fidelity simulation and real-world flight tests, proving its ability to detect, track, and intercept ground and aerial targets under varying weather, lighting, and movement conditions.

Its design emphasizes portability across different UAV airframes, allowing agencies and organizations to integrate the solution into existing fleets without major hardware changes.

The adaptability of the tracking and control modules, combined with the enhanced GCS interface, enables operators to perform complex interception missions with minimal training, ensuring rapid field deployment in defense, security, and public safety operations.

Conference and Competitions

The research and related UAV developments have been presented at various international and national conferences, workshops, and competitions, earning recognition and awards:

- 2023 - “Havq” Competition, **Payload Delivery with UAV**, 2nd place, Yerevan, Armenia.
- 2024 - "Gagarin Science" Conference, “**Optimal Area Coverage Using a Swarm of Drones**”, Moscow, Russia.
- 2024 - "Gagarin Science" Conference, “**Inertial Navigation for Copters**”, Moscow, Russia.
- 2024 - 17th International Annual Student Scientific Conference of RAU, “**Optimal Area Coverage Using a Swarm of Drones**”, Yerevan, Armenia.
- 2024 - 17th International Annual Student Scientific Conference of RAU, “**Inertial Navigation for Copters**”, Yerevan, Armenia.
- 2024 - United Nations / Philippines Workshop on the Applications of GNSS, “**GPS-based 2D Map Creation using Drone Swarm**”, Manila, Philippines.
- 2024 - “**Professionals**” Competition, **Unmanned Aerial Vehicle Operations**, 2nd place, Saint Petersburg, Russia.
- 2024 - United Nations Workshop on GNSS and Related Space Technologies for Urban Sustainability Challenges, “**Drone-Based GPS Object Localization for Urban and Agricultural Monitoring**”, Online.
- 2024 - United Nations Workshop on GNSS and Related Space Technologies for Urban Sustainability Challenges, “**GPS-Enhanced Drone Imaging: Stitching and Change Detection Analysis**”, Online.
- 2024 - 18th International Annual Student Scientific Conference of RAU, “**Autonomous Target Interception with Quadcopters**”, Yerevan, Armenia.
- 2025 - Ivannikov Memorial Workshop, “**Real-time Target Localization Using Gimbaled Laser on UAVs**”, Irkutsk, Russia.
- 2025 - Ivannikov Memorial Workshop, “**Object Re-detection in Aerial Imagery Captured by UAVs**”, Irkutsk, Russia.
- 2025 - 19th International Annual Student Scientific Conference of RAU, “**Autonomous UAV control based on camera video**”, Yerevan, Armenia.

Grants

The research was supported by several grant-funded projects, which provided both financial and technical resources for the development, testing, and dissemination of the results. These grants include:

- 2021 - “**ԲԱԶԵ**”, Project ԲՏԱՆ-ԴՄ-2021/2-1, funded by the Ministry of High-Tech Industry of the Republic of Armenia.
- 2022 - “**Autonomous Aerial Interceptor Drone**”, Project 23DP-1B017, funded by the Ministry of Education, Science, Culture, and Sports of the Republic of Armenia.

- 2023 - "**Development of a UAV Autopilot for Tracking Targets by Using Computer Vision**", PhD grant 23AA-1B005, funded by the Ministry of Education, Science, Culture, and Sports of the Republic of Armenia.
- 2025 - "**Control and Management System for FPV Drone Swarm**", Project 25DP-1B005, funded by the Ministry of Education, Science, Culture, and Sports of the Republic of Armenia.

Publications and Approbation

The results submitted for defense were obtained personally by the applicant. In the published joint works, the formulation and investigation of the problems were carried out through the joint efforts of the co-authors, with the direct involvement of the applicant. In **[1]**, the author configured SIFT, SiamTPN, and TransT object tracking algorithms, conducted UAV flight experiments to collect aerial video data, and developed a unified methodology for combining and comparing tracker performance under real-world conditions. In **[2]**, the author designed and implemented a hyperbolic PDE-based convolutional neural network layer, integrated it into existing deep learning frameworks (ResNet), and performed training and evaluation on the CIFAR dataset to assess performance improvements. In **[3]**, the author carried out a comparative analysis of tracking algorithms, implemented benchmarking experiments, and evaluated their performance on limited-resource hardware. In **[4]**, the author implemented the testing pipeline, developed data augmentation and modification procedures, and conducted comparative experiments on change detection methods. In **[5]**, the author built a UAV platform, developed the main system architecture and onboard code, and conducted flight tests for real-time target localization using a gimbaled laser system. In **[6]**, the author is the sole author of the paper and independently developed the autonomous UAV control method based on camera video, implemented the control algorithms, conducted experimental validation, and prepared the manuscript.

Structure and scope

The work is structured to cover both theoretical foundations and practical applications. **Chapter 1** introduces the research problem, objectives, and scientific novelty. **Chapter 2** reviews related works on visual tracking, UAV control, and ground control systems. **Chapter 3** details the overall system architecture, including modular ROS 2-based software, PX4 integration, and hardware requirements. **Chapter 4** focuses on the perception module, covering object detection and the hybrid tracking pipeline combining YOLO and MixFormerV2/KCF. **Chapter 5** describes UAV control and interception mechanisms, including visual servoing and adaptive PID loops. **Chapter 6** presents the experimental setup, HITL simulations, and real-world flight tests, along with results and performance evaluation. **Chapter 7** discusses conclusions, scientific contributions, and future directions.

2. Review of Related Works

An autonomous UAV interception system integrates visual tracking, flight control, and a ground control interface. Because interception technologies are dual-use, no open-source end-to-end systems are available; therefore, this work reviews relevant subsystems.

Visual tracking is critical for interception. Early correlation-filter methods lacked robustness, while Siamese network trackers improved performance. Transformer-based trackers now achieve state-of-the-art accuracy but are too computationally demanding for lightweight UAVs. To address this, a **hybrid tracker** combining a transformer-based method with a lightweight correlation filter was adopted.

The control system maps visual target information to interception commands. Advanced control strategies were evaluated but found impractical for deployment. A **PID controller** was selected for its simplicity and reliability, with filtering, anti-windup, and axis-specific tuning to ensure stable interception.

QGroundControl was chosen as the Ground Control Station due to its full integration with PX4, compatibility with MAVLink/ROS 2, and extensibility for autonomous interception missions.

3. Overall architecture

The autonomous UAV interception system proposed in this work is built as a tightly integrated hardware-software platform, combining advanced perception modules, robust control logic, and operator supervision tools into a unified operational framework. The architecture follows a layered design, separating perception, decision-making, and actuation components while maintaining low-latency communication between them.

This modular approach enables visual tracking, flight control, and operator interface to be developed, tested, and optimized independently. At the core of the system is a ROS 2-based distributed software architecture running on onboard embedded hardware, which interfaces directly with the PX4 flight stack through MAVLink in both simulated (HITL) and real-world deployments.

From a hardware perspective, the system leverages a combination of commercial off-the-shelf UAV platforms, high-performance embedded computers, and standard communication interfaces. This ensures that the architecture remains cost-effective, replicable, and adaptable to different UAV configurations without sacrificing real-time performance.

The hardware system is designed with a modular and platform-independent hardware structure, enabling integration with a wide range of multirotor configurations.
The minimum required components are:

- **Pixhawk-series flight controller** (PX4-compatible) for stabilization, navigation, and motor control;
- **NVIDIA Jetson Nano** or higher onboard computer for real-time vision and control processing;
- **USB or CSI camera** for target detection and tracking.

The onboard computer executes detection, tracking, and interception logic, while the Pixhawk handles flight stabilization and low-level control through MAVLink communication. This modular architecture allows the system to be deployed on any standard multirotor UAV with minimal hardware adaptation. The onboard and ground system layouts are illustrated in Figures 1 and 2.

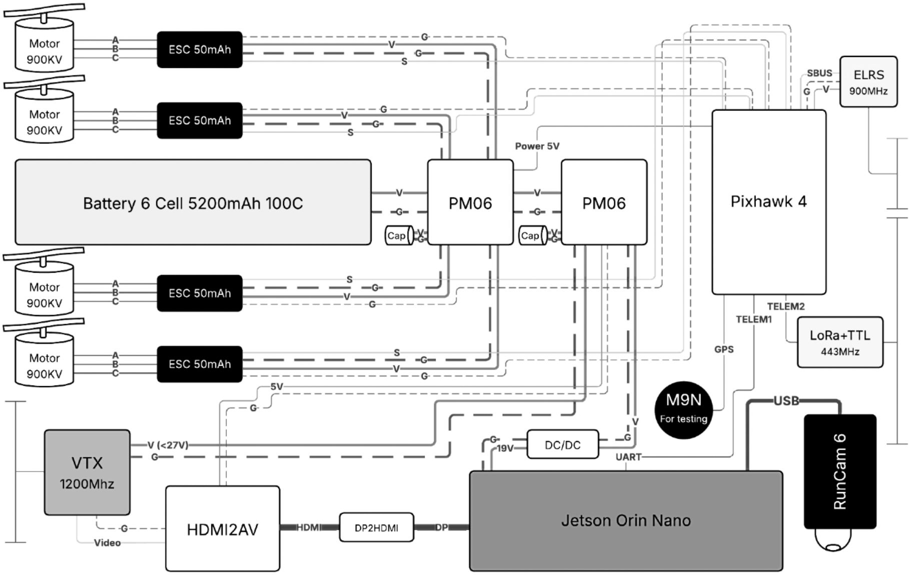


Figure 1: Architecture of the UAV interception platform, including onboard computer (Jetson), flight controller (Pixhawk), camera, power system, and communication interfaces.

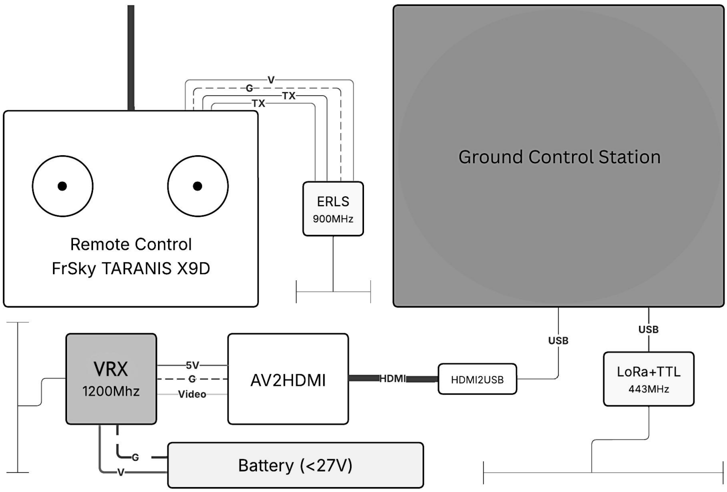


Figure 2: Ground-side system architecture, showing LoRa-based MAVLink telemetry reception, analog video signal conversion chain, and the ground control station.

The software system is built using the ROS 2 Humble middleware. It follows a modular architecture, where each major function (detection, tracking, control) is handled by an independent node running in its own thread. This design enables real-time parallel execution and flexible system scalability.

A structural overview of the software architecture is shown in Figure 3, where each ROS 2 node is represented by a hexagonal shape and interconnected via topic-level communication.

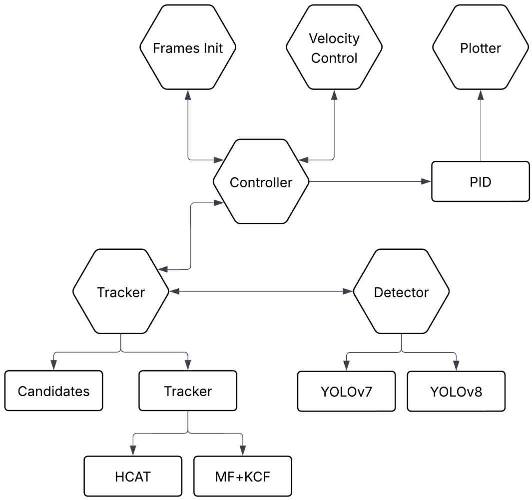


Figure 3: ROS 2 software architecture. Hexagonal blocks represent individual nodes, and double arrows denote communication via topics.

The architecture consists of the following key parts:

Frames Init Node: Converts object pixel coordinates from the camera image frame to the UAV's body frame and NED (North-East-Down) coordinate system.

Detector Node: Executes a YOLO object detector and publishes bounding boxes with class labels and tolerance metadata to the custom topic.

Tracker Node: Performs continuous target tracking using the selected tracking method and is activated only after target initialization. If the detector is enabled, the target can be initialized by selecting a detected bounding box or by manually defining a custom box. If the detector is disabled, the operator may define a bounding box manually or click on the video frame, in which case a **candidate extraction** module generates candidate regions and selects the one whose center is closest to the click position. The tracker outputs the target's top-left and bottom-right pixel coordinates at each frame.

Candidate Extraction: Generates object candidate bounding boxes around a user-selected image point when no detector output is available. The module crops multiple regions of interest (ROIs) at increasing scales centered on the click position, performs edge-based segmentation using Canny edge detection and morphological filtering, extracts external contours, and converts them into bounding boxes. Each candidate is scored using a weighted combination of shape solidity, edge density (Edge Boxes-inspired score), image sharpness, and distance from the click location. The highest-scoring candidate across all ROI scales is selected and returned as the initialized target bounding box.

Controller Node: Implements the high-level control logic. It receives tracking data and computes target-relative roll, pitch, yaw, and thrust using PID controllers. These values are passed to the Velocity Control node.

Velocity Control Node: Converts control outputs into PX4 attitude setpoints and publishes them to the uORB topic.

Plotter Node: A debugging and visualization tool that subscribes to controller outputs and system states to produce real-time plots of PID response and tracking performance.

PX4 and uORB Integration

Custom uORB topics were defined for integrating ROS 2 with PX4:

- Used to send target selection coordinates from QGroundControl to the tracker.
- Transmits updated hyperparameters from the GCS to the relevant ROS nodes.

The system uses MicroXRCEAgent to bridge the Jetson's ROS 2 nodes to PX4's uORB messaging system. Most control commands are routed from ROS 2 to PX4 flight modules, using MAVLink as the underlying transport protocol.

4. Tracker and Detector

The perception module consists of two components: the detector and the tracker. The detector identifies and localizes objects in the video stream, providing initial target information. The tracker maintains the target position during the interception process.

The detection module provides the initial target bounding box for the tracker. At the initial stage of this research, YOLOv7 was selected for its balance between accuracy and real-time performance. After the release of YOLOv8, which represented the state of the art at the time, the module was updated to integrate YOLOv8, benefiting from its improved accuracy and architectural refinements while maintaining high FPS suitable for UAV deployment. Subsequent YOLO release YOLOv9 offered higher accuracy but significantly lower FPS on the embedded hardware[1], making YOLOv8 the preferred choice for maintaining real-time performance.

The detectors were fine-tuned on a combination of Microsoft COCO and VisDrone, selecting only the person and car classes, and a custom AirSim-generated UAV dataset, which was necessary because YOLO's predefined classes do not include UAVs, and tailored data was required for interception scenarios.

The detector is capable of identifying predefined object categories such as vehicles, people, and UAVs. This output not only serves as a direct perception layer for the operator but also initializes the tracker.

[1] Jocher, G., Chaurasia, A., & Qiu, J. (2023). *YOLOv8 vs YOLOv9: A Technical Comparison for Object Detection.* Ultralytics YOLO Docs. Available [Online] https://docs.ultralytics.com/compare/yolov8-vs-yolov9/

The models are converted to TensorRT using FP16 precision to reduce inference latency. Object detection operates asynchronously from the tracking module, publishing bounding boxes to a shared ROS 2 topic. On the GCS screen, the operator can view the detected bounding boxes. The operator can manually select a target by clicking on the desired object on the screen. The algorithm then automatically chooses the detected box whose center is closest to the clicked position, based on Euclidean distance.

The tracking module combines two complementary approaches with different computational characteristics. MixFormerV2-S, a transformer-based tracker, provides high accuracy under occlusion, scale variation, or distractor interference. Its attention mechanism enables context-aware localization but incurs a computational cost of approximately 4.5 GFLOPs per forward pass, which can reduce real-time performance on resource-constrained embedded platforms without hardware-specific optimization. In contrast, the KCF tracker operates at very high frame rates with minimal CPU load and is well-suited for stable-appearance segments of the trajectory.

Adaptive Switching with Perceptual Hashing. To balance accuracy and computational efficiency, an adaptive bidirectional switching mechanism was employed within the frames of this work. At each step:

- ROIs from the current and previous frames are hashed using perceptual hashing (pHash).
- The Hamming distance between hashes is compared to a threshold T.
- If the difference exceeds T, indicating a significant appearance change or potential drift, the system switches to MixFormerV2-S to re-acquire a reliable bounding box.
- If the difference is below T, KCF is used to maintain high-speed tracking.
- When switching from MixFormerV2-S back to KCF, the correlation filter is reinitialized with the most recent high-confidence bounding box.

This ensures that the heavy transformer-based model is activated only when necessary, reducing the average processing time while maintaining high tracking accuracy.

Tracker Evaluation. A two-stage evaluation of tracking algorithms was conducted to determine the most effective approach for real-time UAV interception.

In the first stage, several correlation-filter-based trackers (MOSSE, KCF, CSRT, DSST, ECO) were evaluated on the UAV123 and VisDrone-SOT datasets using a PC equipped with an Intel i7-11th-generation CPU, an NVIDIA RTX 3060 GPU, and 32 GB RAM. This environment enabled rapid prototyping, controlled benchmarking, and extensive parameter tuning, which would have been significantly more difficult and time-consuming if conducted directly on the Jetson platform. Once promising candidates were identified, the same experiments were subsequently replicated on an NVIDIA Jetson Orin Nano to assess performance under embedded hardware constraints.

Implementations were optimized in C++ for maximum performance, with KCF, DSST, and ECO implemented from scratch based on original publications. Evaluation metrics included accuracy, robustness, and frame rate. The results showed that while

MOSSE and DSST offered high speed, their accuracy was insufficient for interception tasks. The custom KCF implementation achieved the best balance between accuracy and speed, making it the selected correlation filter for the next stage.

In the second stage, transformer-based trackers were compared, including MixFormerV2, HCAT, and ViT Tracker. Official implementations with CUDA/TensorRT support were used to ensure optimal performance. The evaluation showed that MixFormerV2 provided the best overall accuracy and robustness, although at a high computational cost.

A more detailed analysis of the experimental setup, evaluation methodology, and results is provided in the main text of the thesis.

Table 1. Comparison of the Hybrid tracking method with different thresholds T, with MixFormerV2, KCF, and HCAT on UAV123 and VisDrone-SOT datasets on Jetson Orin Nano.

	UAV123 [CPU/GPU]							VisDrone-SOT [CPU/GPU]						
	% of MF[2]	↑A (%)	↑R (%)	↑AUC-A (%)	↑AUC-R(%)	↓DRE (%)	↑FPS	% of MF	↑A (%)	↑R (%)	↑AUC-A (%)	↑AUC-R(%)	↓DRE (%)	↑FPS
KCF	0	53.7	41.8	43.8	34.1	58.1	174	0	60.2	57.5	48.4	46.2	42.5	153
MixFormerV2	100	79.7	80.7	64.1	65	19.3	34	100	68.7	69.6	54.8	55.5	30.4	31
HCAT	0	75.2	76.1	60.7	61,4	23.9	33	0	74.6	74.6	58.3	58.4	25.4	33
KCF-MF (T=2)	91.8	77.8	78.9	63.1	63.6	20.4	46	71.5	67.9	67.4	54.1	54.0	31.2	60
KCF-MF (T=5)	84.1	76.4	77.2	61.3	62	22.8	54	62.2	66.4	66.3	52.3	52.4	33.7	68
KCF-MF (T=10)	72.9	69.5	69.3	55	55	30.6	82	30.4	59.9	58.9	48.1	47.4	41.1	113
KCF-MF (T=15)	28.3	63	62.1	49	48.3	38	110	14.9	54.1	53	44.2	44.1	48	137
KCF-MF (T=20)	16.2	60.8	59.9	46.2	45.5	41.9	128	8.5	52.6	51.8	42.3	42.1	52.7	152

Building on these findings, a hybrid tracking approach was developed that combines the speed of KCF with the robustness of MixFormerV2. Switching between trackers is controlled by a perceptual hashing-based similarity metric, with a tunable threshold determining when MixFormerV2 is used. Threshold values of 5 and 10 were selected for experiments, representing trade-offs between accuracy and speed. Results on PC show that the hybrid method with T=5 retains accuracy within 1-2% of MixFormerV2 while increasing FPS by 26-36%.

Experiments on the Jetson Orin Nano platform (Table 1) confirmed the method's suitability for onboard UAV deployment. While MixFormerV2 operates at ~34 FPS, the hybrid tracker with T=5 achieves up to 54-68 FPS with minimal loss in accuracy. Higher thresholds further increase speed, but at the cost of a corresponding drop in accuracy.

The hybrid method enables fine-tuning of performance according to mission requirements, making it adaptable for high-speed ground and aerial target interception, where low latency is crucial.

5. Control and Interception Mechanism

The interception behavior of the UAV is governed by a visual servoing architecture

[2] '% of MF' indicates the proportion of frames tracked by MixFormerV2, with the remainder tracked by KCF.

that tightly couples object localization in the camera frame with real-time flight control. The control pipeline consists of 3 main stages: **Rotation Vector Calculation**, **Outer Loop** (yaw and pitch calculation), and **Inner Loop** (roll and thrust control).

The first stage of the interception mechanism involves transforming image-based target coordinates into 3D angular directions relative to the UAV. This is essential for generating control signals that steer the UAV toward the selected object.

When the tracker identifies a target in the image frame, it provides the center point of the bounding box in pixel coordinates (u, v). To convert this 2D location into a 3D direction in the UAV's reference frame, a multi-step transformation pipeline is used.

Projection to the Ray in the Camera Frame

Let f_x and f_y be the focal lengths of the camera, with c_x and c_y representing the optical center. The pixel is projected into a unit direction vector (ray) in the camera's coordinate system using the calibrated pinhole model:

$$r_c = \begin{bmatrix} \frac{u-c_x}{f_x} & \frac{v-c_y}{f_y} & 1 \end{bmatrix}^T \quad (1)$$

Then we can calculate the normalized vector by dividing r_c by its length:

$$\hat{r}_c = \frac{r_c}{\|r_c\|} \quad (2)$$

Transformation to UAV NED Frame

The resulting ray is transformed from the camera frame to the UAV's body-aligned North-East-Down (NED) frame using TF2[3] transforms. This transformation accounts for the camera's pose relative to the UAV body, and ensures that all angular calculations are consistent with flight control conventions. We know UAV orientation in space (R_{NED}^{body}) from IMU and camera direction from the UAV's frame (R_{body}^{cam}). So, we can calculate ray coordinates in the UAV's NED system:

$$R_{NED}^{cam} = R_{NED}^{body} \cdot R_{body}^{cam} \quad (3)$$

$$\hat{r}_d = R_{NED}^{cam} \cdot \hat{r}_c \in \Re^3 \quad (4)$$

Outer Loop: Yaw and Pitch Calculation

The 3D vector in NED coordinates is normalized (because we only applied rotation on the normalized vector) and used to compute the yaw (ψ) and pitch (θ) angles to the target:

$$\hat{r}_d = [x \;\; y \;\; z]^T \quad (5)$$

$$\psi = atan2(y, x) \quad (6)$$

$$\theta = atan2(-z, \sqrt{x^2 + y^2}) \quad (7)$$

These angles represent the desired change in UAV orientation required to align with the target direction.

[3] https://docs.ros.org/en/humble/Concepts/Intermediate/About-Tf2.html

Rotation Process

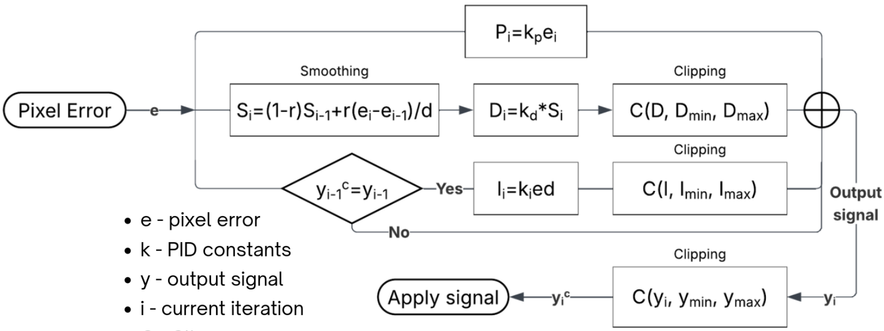
The resulting yaw (ψ) and pitch (θ) values are fed into a custom rotation scheduling algorithm proposed in this work, which smoothly adjusts the UAV's orientation over multiple frames. The algorithm operates as follows:

- Limiting the maximum pitch rotation per control cycle to a predefined threshold by decomposing large pitch commands into multiple incremental rotations;
- Deferring yaw adjustment until the previous yaw rotation is completed;
- This estimation loop is executed in real-time and repeated at each control cycle to ensure continuous alignment with the moving target.

These methods are newly developed for this thesis and represent our original contribution to the control of UAV orientation.

While pitch and yaw angles are derived directly from the object's direction vector, roll and thrust commands are generated through feedback-based PID control (inner) loops, which have also been developed as part of this work and represent a new contribution. These loops regulate the UAV's alignment with the target using its position within the camera frame.

Figure 4 illustrates **a discrete PID control loop** that converts pixel error into a corrective control signal (roll or thrust). The proportional path reacts immediately to the current pixel error, while the derivative path uses a smoothed error change to improve stability and reduce noise sensitivity. The integral path accumulates error over time but is conditionally updated to avoid windup when the output is saturated.



- e - pixel error
- k - PID constants
- y - output signal
- i - current iteration
- C - Clip
- S - Smoothing
- r - Smoothing factor

Figure 4. PID control loop

All contributions are clipped to predefined limits and summed to produce a bounded output that drives the system toward minimizing the pixel error. The only distinction between the roll and thrust PID controllers lies in their respective gain coefficients; otherwise, their structure and functionality are identical.

The Roll PID controller minimizes the rotational alignment error, which is the angular deviation between the object's center and the UAV's dynamically rotated horizon line.

The Thrust PID controller minimizes the vertical offset between the expected interception pitch line and the target's projected location.

As shown in Figure 5, the following control relationships are enforced:

- **White lines** represent the camera's vertical axis and the dynamically rolled vertical line.
- **The rectangle** and **the star mark** the tracked object and its center.
- **The cross** is the projection of the object center onto the rolled vertical line.
- **The central circle** indicates the direction of optical interception.
- **The gray dashed line** shows the roll error (minimized by roll PID)
- **The white dot-dashed line** shows the thrust error (minimized by thrust PID)
- **The black dotted line** is the critical pitch threshold line.

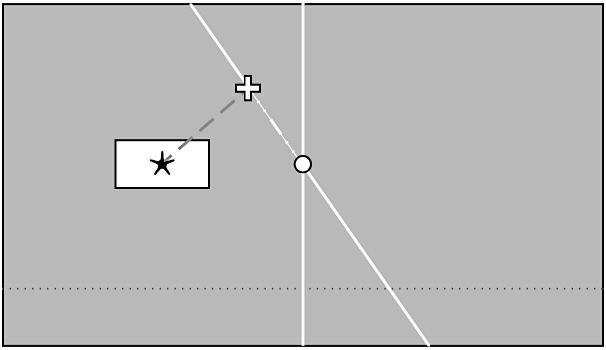


Figure 5: Visual representation of the visual servoing control loop.

In optimal alignment, the star moves toward the cross mark (i.e., the object center aligns with the rolled vertical line), and the cross mark moves toward the central circle (i.e., aligned intercept trajectory). The control system ensures that all three converge, forming a visually stable and geometrically consistent intercept maneuver.

A customized version of QGroundControl (QGC) is integrated into the system to enable effective mission monitoring and in-flight parameter control. Given that the UAV operates on the PX4 autopilot stack, which natively supports MAVLink and ROS 2 middleware, QGC serves as a compatible and extensible interface.

6. Experimental Setup

To validate the proposed UAV interception system, a series of experiments was conducted in both simulated and real-world conditions. The evaluation process was structured to isolate and test each subsystem under controlled conditions before integrating them into a complete interception loop.

Testing was carried out in two stages:

1. **HITL simulation** - assessing the complete interception control loop in Gazebo Classic with 2496 distinct test configurations, covering varying target speeds, approach angles, and visibility conditions.
2. **Real-world flight tests** - verifying system performance with actual UAVs in diverse environmental and operational scenarios.

Each stage was designed to provide both quantitative and qualitative metrics, allowing for the iterative refinement of algorithms and parameters.

HITL simulation was used to evaluate the interception pipeline under controlled yet realistic conditions, leveraging a framework developed using Gazebo Classic in conjunction with the PX4 flight stack. This setup enabled the testing of the full vision-control loop with accurate flight dynamics, real-time camera streaming, and onboard computation identical to that in field deployment.

The simulation world consisted of a flat ground plane and a single SUV model acting as the moving target. The UAV model was a PX4-compatible quadrotor connected to a Pixhawk flight controller in HITL mode. The camera feed from Gazebo was streamed through an HDMI-to-USB converter to the onboard computer, mimicking real-world video capture latency. ROS 2 nodes ran on the onboard computer, processing frames in real time and issuing control commands back to PX4.

Scenario Parameters

A total of 2496 distinct scenarios were generated by varying the following parameters:

- **UAV altitude:** 18m, 36m, 80m, 200m
- **Initial UAV-to-target horizontal distance:** 2m, 11m, 21m, 41m, 101m
- **Initial UAV yaw angle:** 0°, −25.8°, +17.2°
- **Target motion direction relative to the UAV:** toward, away, perpendicular, diagonal relative to the UAV
- **Target velocity:** 0m/s, 5m/s, 10m/s, 15m/s
- **Wind:** 0m/s, 1m/s, 3m/s, 5m/s

Each scenario included a predefined bounding box for tracker initialization to ensure reproducibility. All scenarios were required to have the target visible at the start.

Each scenario was evaluated using the following **success criteria**:

- The interception is successful if the UAV makes contact with the SUV within 30 seconds.
- The test is considered a failure if the UAV hits the ground or exceeds the time limit.
- After each outcome, the pipeline restarts with the next configuration.

Simulation Results

Performance across target speed categories is summarized in Table 2. The results indicate that the system achieved performance for stationary and low-speed targets.

Failures occurred primarily in high-speed scenarios (15m/s) when the SUV was moving directly toward the camera. In these cases, rapid apparent size growth and high optical flow made stabilization and trajectory prediction more challenging, occasionally causing late reactions or ground impact. A more detailed analysis of these experimental scenarios and their outcomes is presented in the main text of the thesis.

Table 2: Interception performance by target speed in HITL.

Target Speed (m/s)	Number of Scenarios	Success (%)	Avg. Time (s)	Ground Impacts	Timeouts
0	1920	100	8	0	0
5	7680	98	13.1	154	3
10	7680	93	16.4	392	141
15	7680	78	21.3	799	893

HITL simulation behavior closely matched results from real flights[4]. The framework proved effective for iterative tuning of tracking, control, and mission logic before field deployment.

Real-world evaluation was conducted to validate the proposed autonomous interception system under practical operational conditions. The primary test platform was the Reptile X500 multirotor, with additional verification flights performed on Holybro S500 and Holybro X500 frames. Onboard processing was handled by NVIDIA Jetson Nano, Jetson Xavier NX, and Jetson Orin Nano modules, with live video input provided via both USB and CSI cameras.

Flights were performed across a wide range of environmental and mission configurations, including:

- Varying initial yaw, pitch, and roll orientations of the UAV.
- Stationary and moving targets.
- Both ground-based and airborne targets.
- Short and long-range engagements, with varying visibility and occlusion conditions.
- Light to moderate wind, with occasional gusts.

Table 3: Real-world results: interception success rate by target speed.

Target Speed (m/s)	Number of Scenarios	Success (%)	Avg. Time (s)	Ground Impacts	Timeouts
0	70	95.7	5	2	1
5	36	92.7	12	2	1
10	24	83.3	17	2	2
14	20	75	30	3	2

In total, approximately **150 flights** were conducted, encompassing a diverse mix of test cases. For each trial, system logs and onboard video recordings were collected for offline debugging, parameter tuning, and qualitative performance evaluation. A more detailed analysis of real-world experiments is presented in the main text of the thesis.

Results Overview

The system successfully intercepted moving ground targets (Table 3) in the majority

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[4] Rafael Perez-Segui et al., "Bridging the Gap between Simulation and Real Autonomous UAV Flights in Industrial Applications," Aerospace 10, no. 9 (2023): 814, https://doi.org/10.3390/aerospace10090814

of test flights. Overall behavior in real-world conditions closely matched trends observed in the HITL simulation stage.

Environmental Factors

Wind gusts occasionally introduced disturbances into the control loop, causing minor deviations in vehicle motion. Also, direct sunlight striking the camera lens sometimes created glare or lens flares, which could temporarily reduce image clarity and affect visual tracking. Despite these influences, the overall system performance remained stable, and no critical mission failures occurred during the test campaign.

7. Discussion and Conclusion

In conclusion, the objectives and novel contributions outlined in this thesis were successfully realized:

- **A hardware-agnostic UAV interception framework** was designed and implemented, demonstrating compatibility with multirotor platforms equipped with standard flight controllers and onboard computing systems.
- **A real-time hybrid tracking** pipeline was developed and deployed on embedded UAV hardware. The system operated reliably under onboard computational constraints and supported operator-defined arbitrary targets, enabling flexible and practical interception scenarios.
- **A target acquisition algorithm** combining deep learning-based object detection with a low-latency tracking mechanism was successfully implemented.
- **A dual-loop adaptive PID control system** incorporating yaw and pitch guidance, independent roll and thrust control, and real-time in-flight parameter tuning via MAVLink was designed and validated.
- **A comprehensive evaluation framework** was established, integrating HITL simulations with diverse target dynamics and real-world field experiments. The results confirmed the robustness, effectiveness, and real-world applicability of the proposed UAV interception system under challenging environmental conditions.

This research is currently being extended into a **swarm-based UAV interception project**, aiming to coordinate multiple autonomous interceptors for simultaneous target engagement and enhanced operational efficiency. This ongoing work builds directly upon the single-UAV system developed in this thesis and represents the next phase of practical deployment and algorithmic advancement.

List of the author's publications

[1] V. Melkonyan, V. Sahakyan, L. Kirakosyan, O. Hovhannisyan. "**Comparison of Single Object Tracking Algorithms on Video Sequences Captured from UAV.**" Vestnik of the Russian-Armenian University (2022): 67-75.

Contribution: Configured SIFT, SiamTPN, and TransT object tracking algorithms, conducted UAV flight experiments to collect aerial video data, and developed a unified methodology for combining and comparing tracker performance under real-world conditions.

[2] V. Sahakyan, V. Melkonyan, G. Gharagyozyan, A. Avetisyan. "**Enhancing Image Recognition with Pre-Defined Convolutional Layers Based on PDEs.**" Programming and Computer Software. Vol. 49. No. 3. 2023: 192-197.

Contribution: Designed and implemented a hyperbolic PDE-based convolutional neural network layer, integrated it into existing deep learning frameworks (ResNet), and performed training and evaluation on the CIFAR dataset to assess performance improvements.

[3] A. Sardaryan, V. Sahakyan, V. Melkonyan, S. Sargsyan. "**An Accurate Real-Time Object Tracking Method for Resource Constrained Devices.**" Proceedings of the Institute for System Programming of the RAS. Vol. 36, issue 3. 2024: 283-294.

Contribution: Conducted the comparative analysis of tracking algorithms, implemented benchmarking experiments, and evaluated their performance on limited-resource hardware.

[4] A. Fahradyan, T. Baghdasaryan, V. Melkonyan, V. Sahakyan, L. Kirakosyan, O. Hovhannisyan, S. Sargsyan, A. Darbinyan. "**Comparing and improving change detection methods.**" Vestnik of the Russian-Armenian University (2024): 37-43.

Contribution: Developed the evaluation pipeline and data augmentation procedures for comparative change detection experiments.

[5] V. Sahakyan, V. Melkonyan, S. Sargsyan. "**Локализация целей в реальном времени на БПЛА с лазерным дальномером на подвесе.**" Proceedings of the Institute for System Programming of the RAS. Vol. 37, issue 4, part 1. 2025: 189-198.

Contribution: Built the UAV, developed the main system architecture and code, and conducted flight tests.

[6] V. Melkonyan. "**Autonomous UAV Control Based on Camera Video.**" Vestnik of the Russian-Armenian University (2025): 17-25.

Contribution: Sole author; designed and implemented the autonomous control system, conducted experiments, and prepared the manuscript.

Ամփոփում

Վահագն Գևորգի Մելքոնյան

Թիրախին հետևող ԱԹՍ ավտոպիլոտի մշակում համակարգչային տեսողության կիրառմամբ

Վերջին երկու տասնամյակներում անօդաչու թռչող սարքերը (ԱԹՍ) վերածվել են ժամանակակից տեխնոլոգիաների կարևոր բաղադրիչի՝ լայն կիրառություն գտնելով անվտանգության, արդյունաբերական, գիտական և ռազմական ոլորտներում: Համակարգչային տեսողության, ինքնավար կառավարման և ներկառուցված հաշվարկային համակարգերի արագ զարգացումը հնարավորություն է տվել ԱԹՍ-ներին իրականացնել բարդ գործողություններ՝ նվազագույն օպերատորային միջամտությամբ:

Տվյալ ատենախոսության նպատակն է մշակել ինքնավար ԱԹՍ հարվածողական համակարգ, որն ունակ է իրական ժամանակում հայտնաբերել, հետևել և խոցել օդում կամ գետնի վրա շարժվող և անշարժ թիրախների: Առաջարկվող համակարգը նախատեսված է ապահովելու բարձր ճշգրտություն, կառավարման կայունություն և օպերատորի հետ արդյունավետ փոխազդեցություն դինամիկ միջավայրերում:

Տեխնիկական տեսանկյունից աշխատանքը լուծում է մի շարք հիմնական խնդիրներ՝ կապված տեսողական հետևումն իրական ժամանակում իրականացնելու, սահմանափակ հաշվարկային ռեսուրսների պայմաններում ալգորիթմների արդյունավետության և թիրախի նկատմամբ ԱԹՍ-ի ճշգրիտ ուղղորդման հետ: Այդ նպատակով մշակվել է մոդուլային ծրագրային ճարտարապետություն՝ հիմնված ROS 2 միջավայրի վրա, որն ինտեգրվում է PX4 ավտոպիլոտի և MAVLink հաղորդակցման պրոտոկոլի հետ:

Հետազոտության շրջանակներում իրականացվել են հետևյալ հիմնական աշխատանքները.

- **Տեսողական հայտնաբերում և դասակարգում**
  ԱԹՍ-ի վրա ինտեգրվել են YOLOv7 և YOLOv8 օբյեկտների հայտնաբերման մոդելներ՝ fine-tuning իրականացված Microsoft COCO, VisDrone և AirSim միջավայրում ստեղծված UAV տվյալների հավաքածուների վրա:
- **Կայուն և արդյունավետ հետևում**
  Մշակվել է MixFormerV2-S և KCF ալգորիթմների վրա հիմնված հիբրիդային հետևման մեթոդ, որը համատեղում է բարձր ճշգրտությունը և հաշվարկային արդյունավետությունը՝ ապահովելով ինչպես class-agnostic, այնպես էլ օպերատորի կողմից ընտրված կամայական թիրախների հետևում:
- **Խոցման կառավարման ալգորիթմներ**
  Առաջարկվել է տեսողական սերվո-կառավարման ճարտարապետություն yaw և pitch ուղղությունների հաշվարկով արտաքին օղակում և roll ու thrust ՀԻԴ կարգավորիչներով ներքին

օդակում, ինչը ապահովում է թիրախի նկատմամբ ԱԹՍ-ի կայուն և հարթ մոտեցում:

- **Գետնային կառավարման կայանի հնարավորությունների ընդլայնում**
  Ընդլայնվել է QGroundControl միջավայրը՝ ներառելով իրական ժամանակում վիդեո հոսք, մեկ սեղմումով թիրախի ընտրություն, ժեստային կառավարում և թռիչքի ընթացքում պարամետրերի դինամիկ փոփոխություն:
- **Փորձարկում և գնահատում**
  Համակարգը գնահատվել է Gazebo Classic միջավայրում իրականացված 2496 HITL սիմուլյացիոն սցենարներով, ինչպես նաև իրական դաշտային թռիչքներով տարբեր ԱԹՍ հարթակների, թիրախների և շրջակա միջավայրի պայմաններում:

Աշխատանքի գիտական նորույթը ինքնավար ԱԹՍ ինտերցեպցիայի ամբողջական համակարգի մշակումն է, որը միավորում է տեսողական հայտնաբերումը, հիբրիդային հետևումը, ադապտիվ կառավարման ալգորիթմները և օպերատորի հետ իրական ժամանակում փոխազդեցությունը մեկ միասնական ճարտարապետության շրջանակում: Առաջարկվող լուծումը ապացուցել է իր կիրառելիությունը, ինչպես բարձր ճշգրտության սիմուլյացիոն միջավայրում, այնպես էլ իրական թռիչքային պայմաններում՝ ապահովելով համակարգի գործնական կիրառման հնարավորությունը անվտանգության և պաշտպանական խնդիրների լուծման համար:

Заключение

Мелконян Ваагн Геворкович

Разработка автопилота БПЛА для сопровождения целей с применением компьютерного зрения

За последние два десятилетия беспилотные летательные аппараты (БПЛА) превратились в важный компонент современных технологий и нашли широкое применение в сферах безопасности, промышленности, науки и обороны. Быстрое развитие компьютерного зрения, автономных систем управления и встроенных вычислительных платформ позволило БПЛА выполнять сложные задачи при минимальном участии оператора.

Целью данной диссертационной работы является разработка автономной системы перехвата БПЛА, способной в реальном времени обнаруживать, сопровождать и направляться к неподвижным и движущимся наземным и воздушным целям. Предлагаемая система ориентирована на обеспечение высокой точности, устойчивости управления и эффективного взаимодействия с оператором в динамических условиях эксплуатации.

С технической точки зрения в работе решается ряд ключевых задач, связанных с реализацией визуального сопровождения в реальном времени, эффективной работой алгоритмов в условиях ограниченных вычислительных ресурсов и точным управлением БПЛА относительно выбранной цели. Для этого разработана модульная программная архитектура на базе ROS 2, интегрированная с автопилотом PX4 и протоколом связи MAVLink.

В рамках работы реализованы следующие основные направления:

- **Визуальное обнаружение и классификация объектов**
  На борту БПЛА интегрированы модели обнаружения объектов YOLOv7 и YOLOv8, дообученные на наборах данных Microsoft COCO, VisDrone и специализированном UAV-датасете, созданном в среде AirSim.
- **Устойчивое и вычислительно эффективное сопровождение**
  Разработан гибридный алгоритм сопровождения на основе MixFormerV2-S и KCF, сочетающий высокую точность и низкую вычислительную сложность и поддерживающий как class-agnostic сопровождение, так и сопровождение целей, выбранных оператором.
- **Алгоритмы управления перехватом**
  Предложена архитектура визуального сервопривода, включающая расчёт углов yaw и pitch во внешнем контуре управления и использование ПИД-регуляторов по каналам roll и thrust во внутреннем контуре, что обеспечивает плавное и устойчивое наведение БПЛА на цель.
- **Расширение наземной станции управления**
  Модифицирован QGroundControl с поддержкой видеопотока в реальном времени, выбора цели одним нажатием, жестового управления и динамической настройки параметров полёта.
- **Экспериментальная проверка и оценка**
  Система протестирована в среде Gazebo Classic с использованием 2496 HITL-сценариев, а также в ходе реальных лётных испытаний на различных платформах БПЛА, при разных условиях окружающей среды и типах целей.

Научная новизна работы заключается в разработке целостной автономной системы перехвата БПЛА, объединяющей визуальное обнаружение, гибридное сопровождение, адаптивные алгоритмы управления и взаимодействие с оператором в реальном времени в рамках единой архитектуры. Предложенное решение продемонстрировало практическую применимость как в высокоточной имитационной среде, так и в реальных лётных условиях, подтверждая возможность его использования для решения задач в области безопасности и обороны.