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RELIABILITY ENHANCEMENT OF AUTOMATED TARGET DETECTION AND SHOOTING SYSTEMS USING MATHEMATICAL MODELLING AND SIMULATION

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ABSTRACT

This paper helps to improve reliability for a considered Automated Target Detection and Shooting Systems (ATDS) by using mathematical modeling and simulation. In the proposed model, the methodology of object detection based on the blob concept is combined with the parametric feature extraction and the Bag of Features (BOF)-based classification to enhance the object detection accuracy and decrease the false alarms. Reliability in decisions is produced by a statistical validation technique with using positive and negative predictive values. Here, a trajectory modeling system considered/modeled on the basis of the dynamic motion equations enhances accuracy in firing. Simulation experiments show that there are great results on classification, detection reliability and overall system efficiency. The framework offers an effective and scalable solution to real-time defense and surveillance applications in different environmental conditions.

KEY WORDS: *ATDS, Bag of Features, Simulation, Reliability, Support Vector Machine*

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1. INTRODUCTION

The Automated Target Detection and Shooting Systems (ATDS) have now become essential in the current defense and surveillance uses, as well as in the modern defense and surveillance applications, including the automation of the target recognition, tracking, and shooting systems. Noise, clutter and dynamic target behavior are part of the inherent difficulty of target detection in real-world situations. The systems based on IR and vision should be capable of differentiating targets against complex backgrounds and reducing the number of false alarms, directly affecting the performance of the systems (Cao et al., 2024). Such restrictions may cause wrong classification and decreasing reliability of operations. Besides detection, performance of ATDS hinges on correct trajectory modeling, and firing mechanism. The environmental conditions and system parameters may cause large deviations in projectile paths, which can influence the precision in targeting. Mathematical modeling and simulation offer a methodological way of studying the behavior of a system and enhancing its reliability. These methods allow testing under different conditions and finding the most crucial failure points (Wang et al., 2023). Although these developments have occurred, most of the current studies concentrate on the individual components but not a whole system-level approach. Thus, this study suggests a composite model that integrates detection, classification and modeling the trajectory to improve overall reliability of ATDS.

2. LITERATURE REVIEW

The recent advancements in automated target detection systems have improved accuracy and operational efficiency, although reliability under real-world conditions remains a concern. Deep learning models, especially for infrared detection, have shown promise in target extraction and background noise reduction, despite challenges in complex environments(Cao et al., 2024). Object detection techniques based on deep learning yield good results but are sensitive to data quality(Butt et al., 2023). A notable research focus is managing uncertainty in detection systems through probabilistic and stochastic modeling, enhancing reliability in decision-making for defense applications (Huang et al., 2023; Brucks et al., 2023). Radar systems benefit from advanced signal processing and machine learning, improving detection accuracy(Xu et al., 2024). Investigations into multi-target tracking and hybrid systems aim to boost performance, particularly for dynamic targets (Chen et al., 2024). Simulation methods allow for assessing system performance without implementation(Zhang & Zhang, 2023). However, most studies focus on specific elements rather than overall system reliability, highlighting the need for an integrated approach that combines mathematical modeling, simulation, and reliability analysis to enhance automated target detection and shooting systems.

3. RESEARCH METHODOLOGY

The proposed methodology involves the combination of image processing, feature-based classification and mathematical modeling with simulation to increase the reliability of the Automated Target Detection and Shooting Systems (ATDS). The entire architecture comprises three key steps namely: (i) object detection through the use of blob analysis, (ii) feature extraction and classification, and (iii) trajectory modeling and simulation.

3.1 OBJECT DETECTION AND BLOB ANALYSIS

The input video acquired from surveillance systems is first pre-processed by converting RGB frames into grayscale. Background modelling is performed by averaging initial frames:

$$B(x,y) = \frac{1}{N}\sum_{k=1}^{N} I_k(x,y)$$

Where Ik(x,y) represents the pixel intensity of the kth frame and B(x,y) is the estimated background

Object segmentation is achieved using background subtraction:

$$D(x,y) = |I(x,y) - B(x,y)|$$

A binary mask is generated using a threshold T:

$$M(x,y) = \begin{cases} 1, if\ D(x,y) > T \\ 0, \quad Otherwise \end{cases}$$

Blob attraction is further refined using the Laplacian of Gaussian (LoG) operator:

$$\nabla^2 I = \frac{\delta^2 I}{\delta x^2} + \frac{\delta^2 I}{\delta y^2}$$

Noise is reduced using mean and median filters, and connected components (blobs) are identified using 4- or 8-connectivity

3.2 FEATURE EXTRACTION AND CLASSIFICATION

Once blobs are extracted, several geometric and statistical features are computed, including:

- Area (A)
- Centroid (x_c,y_c)
- Major and minor axis lengths (L_{maj}, L_{min})

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A key contribution of this work is the use of **parametric ratios** for classification:

$$R_1 = \frac{A}{L_{maj}}, R_2 = \frac{A}{L_{min}}, R_3 = \frac{L_{maj}}{L_{min}}$$

Additional features such as **tyre detection, inter-tyre distance, and speed estimation** are incorporated. Target speed is calculated as:

$$v = \frac{d}{t}$$

Where d is the distance covered and t is the time derived from frame rate.

For robust classification, the **Bag of Features (BOF)** approach is employed, where feature vectors are clustered using k-means to form a visual vocabulary. Classification is performed using **Support Vector Machine (SVM)**:

$$f(x) = w^T x + b$$

Where w is the weight vector and b is the bias. Additionally, Histogram of Oriented Gradients (HOG) is used for feature representation.

To improve reliability, an imprecise test detector is introduced using:

$$PPV = \frac{TP}{TP + FP}, \qquad NPV = \frac{TN}{TN + FN}$$

Where TP, TN, FP, FN represent true positive, true negative, false positive and false negative respectively.

3.3 TRAJECTORY MODELLING AND SIMULATION

The firing mechanism is modelled using a **6-degree-of-freedom (6-DOF) system**, incorporating translational and rotational motion. The position dynamics are governed by:

$$m\frac{d^2\vec{r}}{dt^2} = \vec{F}$$

Where F includes gravitational and aerodynamic forces.

Projectile motion is further analyzed using velocity components:

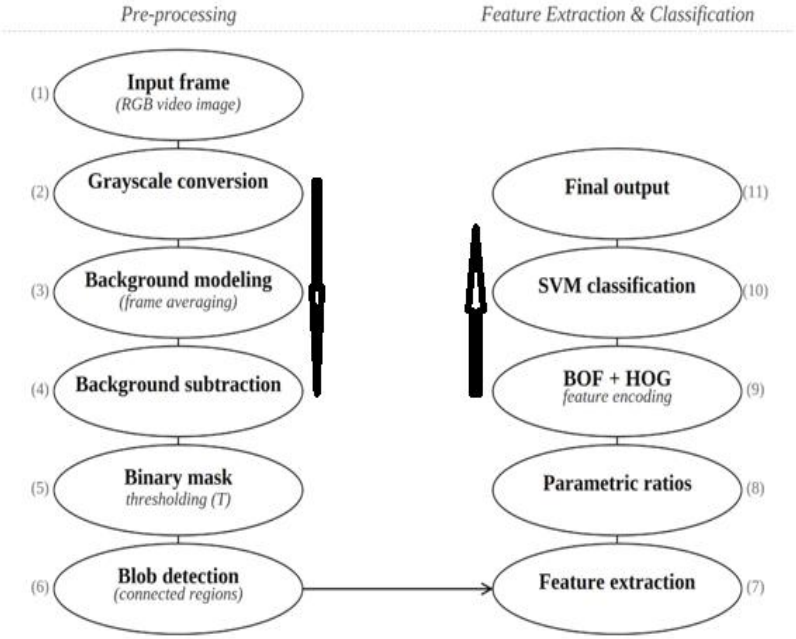
$$v_x = v\cos\theta,\ v_y = v\sin\theta$$

The remaining kinetic energy during flight is given by:

$$KE = \frac{1}{2}mv^2$$

Transformation and rotation matrices are used to determine projectile orientation based on yaw, pitch and roll angles.

3.4 FLOWCHART OF THE PROPOSED METHODOLOGY



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3.5 IMPLEMENTATION AND VALIDATION

The entire methodology is implemented in a MATLAB simulation environment. The system processes video inputs to evaluate detection accuracy, classification efficiency, and trajectory precision. The integration of detection, classification, and trajectory modelling ensures a significant improvement in system reliability, minimizing false alarms and enhancing targeting accuracy.

4. RESULT AND DISCUSSION

The experimental assessment of the proposed Automated Target Detection and Shooting System (ATDS) shows that the accuracy of target detection, the reliability of classification, and the performance of the overall system improve significantly with the use of the combinations of blob analysis, parametric feature modeling, and simulation-based trajectory estimation.

4.1 DETECTION AND CLASSIFICATION PERFORMANCE

The findings indicate that blob-based object detection effectively segments moving objects using parametric feature extraction. The system recognizes targets based on geometric qualities, particularly the area to minor axis ratio, which provides high discriminatory ability across various vehicle classes including cars, buses, and motorcycles (Figure 1). This ratio is robust against scale and illumination changes, making it suitable for surveillance. Experimental results demonstrate that incorporating area thresholds (10,000-80,000+ pixels) and tire-distance features improves classification accuracy. Additionally, tire detection enhances confidence in classification by helping to minimize misclassification of non-target objects.

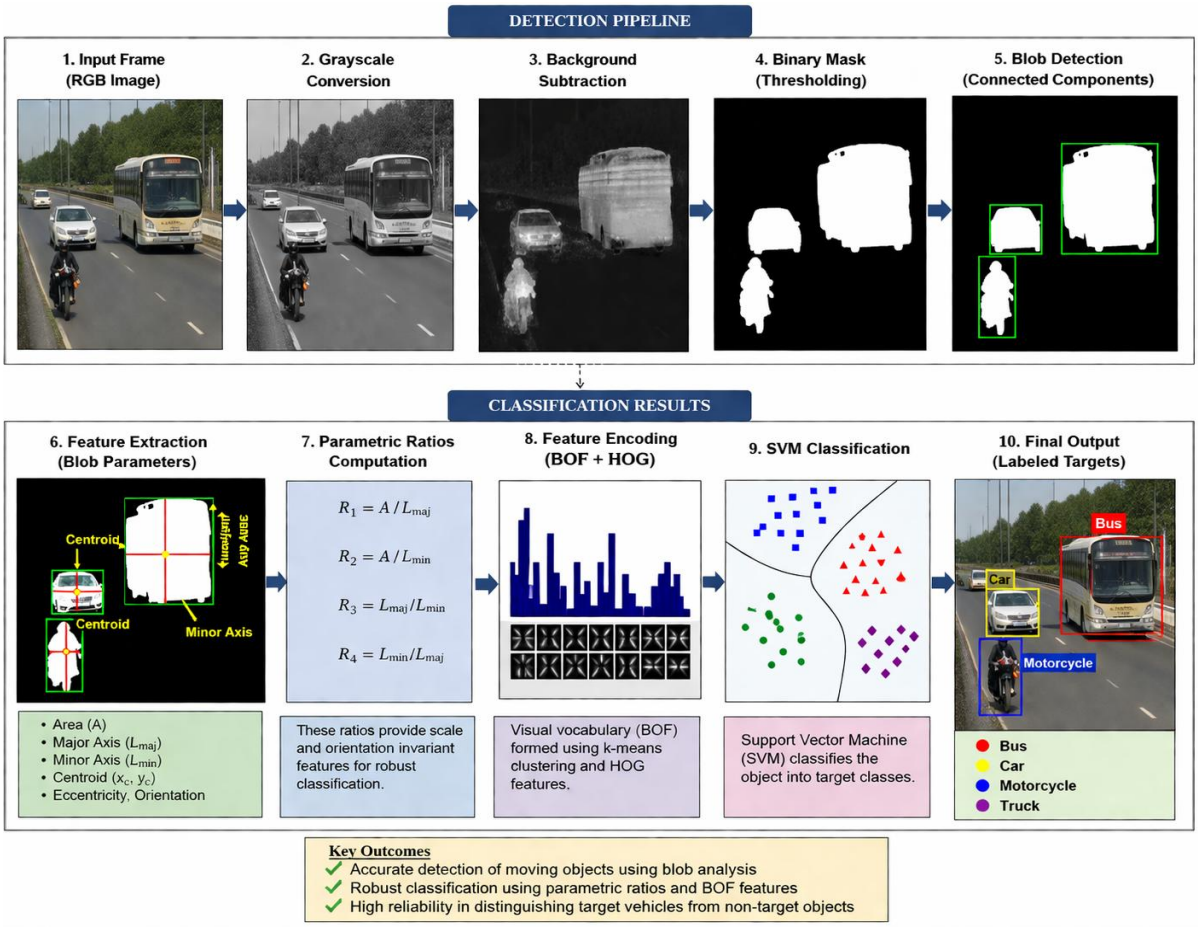


Figure 1: Detection and Classification performance

4.2 ACCURACY ANALYSIS AND COMPARATIVE PERFORMANCE

A comparative study of various methods indicates that the proposed parametric method of blob-based recognition is able to achieve moderate to high accuracy at a relatively low complexity. It is stated that detection accuracy can be approximately 71.5% in the case of CCD cameras and 60% in the case of thermal imaging systems, which exemplifies the effects of the quality of sensors and the environment. But when it is improved with some new features like tire detection and speed estimate, accuracy is much better at 87.5% (CCD) and 71.7% (thermal). An additional enhancement is witnessed with the introduction of the Bag of Features (BOF) technique, which is able to attain up to 90% accuracy in the case of thermal imaging, mainly because it can help to reduce the rate of false alarms. The system also shows true target detection accuracy of 98% and non-target detection accuracy of 82% meaning that it is highly reliable in distinguishing between valid and irrelevant targets.

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Table 1: Comparison between different object detection techniques Vs Developed technique

Method	Accuracy Achieved	Complexity	Edge Detection	Comment
Template Matching	Low	High	No	Requires significant memory capacity and can track both stationary and moving objects effectively
Optical Flow	Moderate	High	No	It delivers complete motion details without pixel loss, though it involves complex computations and high memory consumption.
Frame Difference	High	Low to Moderate	No	This is the simplest approach and performs efficiently in static background conditions. However, its performance decreases when dealing with fast-moving objects
BLOB Analysis (Parametric ratio based)	Moderate (71.5% CCD) (60% - TI)	Low	Yes	Requires comparatively low memory and is suitable for detecting both static and moving objects. High accuracy is achieved with stationary or single targets, but performance declines in multi-target scenarios. Greater precision is obtained using charge-coupled devices (CCD), whereas accuracy is lower with Thermal Imagers (TI).

4.3 RELIABILITY ENHANCEMENT AND SPEED ESTIMATION

The introduction of an inaccurate statistical test detector significantly enhances classification reliability by utilizing Positive Predictive Value (PPV) and Negative Predictive Value (NPV) to reduce false positives and negatives (Figure 2). The system improves decision-making consistency through confidence factors derived from multiple frames, with an optimal confidence threshold between 37.6 and 42.8. It also estimates vehicle speeds between 18 km/h and 35 km/h based on frame-based motion analysis, aiding in trajectory prediction and dynamic adjustment of aiming parameters for increased firing accuracy.

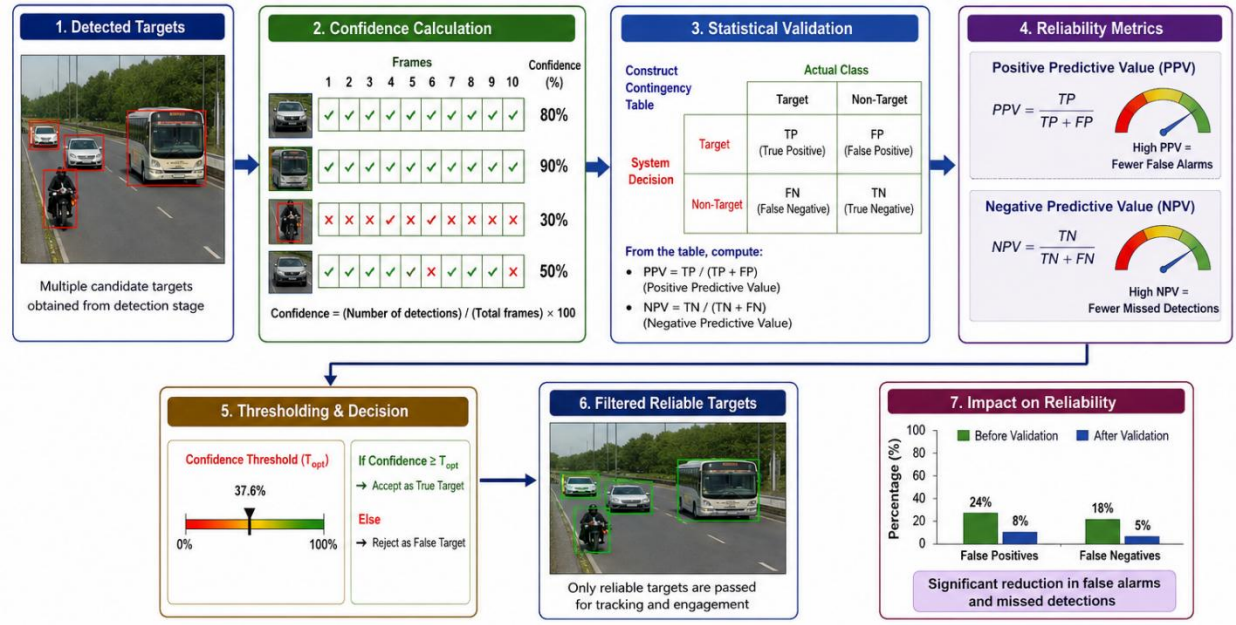


Figure 2: Reliability Enhancement through Statistical validation

4.5 DISCUSSION ON SYSTEM PERFORMANCE AND LIMITATIONS

The findings support the development of a balanced trade-off between accuracy, computational efficiency, and the ability to be applied with the proposed methodology. Blob analysis is simple and has low memory requirements whereas BOF is more costly in terms of computational load. It works exceptionally well when there is controlled lighting, when the target is a single object, under conditions of low contrast thermal imaging, or when it is under controlled surroundings. In addition, classification errors can be caused by similar geometric characteristics of different vehicle classes, such as the overlap between the large cars and the small trucks. Such a limitation implies that there was need to include more features or advanced learning models to enhance discrimination. In general, the combination of the use of the parametric modeling based on blobs, feature fusion, and the use of simulations to analyze data considerably improves the reliability of the ATDS. It is shown that the system has great potential to minimize false alarms, enhance detection, and provide accurate engagement of the target. These findings confirm the efficiency of the suggested solution as a feasible and scalable solution to both real-time defense and surveillance applications.

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5. CONCLUSION

The proposed framework is an effective combination of blob-based detection, parametric feature extraction, and Bag of Features (BOF)-based classification to enhance the accuracy of target recognition and to reduce false alarms. The use of the trajectory modeling and the statistical reliability measures further enhance the performance of the system in different operational environments. The simulation outcomes indicate that there have been significant enhancements in the detection accuracy, classification reliability, and the overall system efficiency.

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