CSE573: Introduction to Computer Vision and Image Processing

Final Project Report

VARLite - A Real-Time Offside Detection System focused on Consumer Hardware

Submitted By:

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1. Overview of the Project

Offside calls remain one of the toughest split-second judgments in soccer, with amateur referees missing roughly **32 %** of tight offsides. Top-tier leagues use Video Assistant Referees (VAR), which depend on video replays and manual line drawing—solutions too resource-intensive for grassroots and low-budget competitions. Our proof-of-concept, **VARLite**, shifts this paradigm: it processes **single frames** (still images) and automatically overlays an offside line at **>20 FPS** on commodity hardware (GTX 1650). By integrating a fine-tuned YOLOv8 detector, precise line-segment extraction, and classic 3D perspective geometry, VARLite demonstrates that reliable offside support can be achieved in real time without a full video pipeline.

2. Approach

2.1 Algorithm Details

1. **Object Detection:**
    - YOLOv8n performs detection of outfield players and goalkeepers along with pitch boundaries (sidelines combined with goal-area edges) through fine-tuning on SoccerNet-v3 Mini data.
2. **Line Extraction:**
    - YOLO creates genuine two-point line segments from detection boxes which target side_top and rect_left categories.
    - The YOLO architecture links two corners together through its horizontal classes from bottom-left to top-right.
    - The vertical detection system links corners between the top left and bottom right of the field.
3. **Field Geometry:**
    - Vanishing Point (V): All vertical segments should be stacked into homogeneous coordinates while SVD calculates their nullspace.
    - Horizon Intersection (P_0): The placement of P_0 occurs through the intersection of a horizontal segment with a chosen vertical segment to determine the reference point on the world plane.
4. **Last-Defender & Lead-Attacker:**
    - The researcher should project the "foot" corners of each player onto the dominant touchline before measuring their perpendicular distance from a specified image reference point.
    - Among the team players the defensive player who holds the most ground distance while the attacking player with the extreme distance becomes lead attacker.

- Use the vanishing point to extend the measured distances across the imagery to visualize defense and offside lines.

5. **Offside Decision:**
    - Compare the projected attacker vs. defender lines:
        - If attacker is closer to the goal line than defender, flag OFFSIDE.
        - Otherwise, flag ONSIDE.

2.2 Independently Coded Components

- BBox to Line Conversion: The system requires improved corner selection algorithms for turning YOLO detection output into precise 2-point segments.
- SVD-Based Vanishing-Point Solver: A custom implementation uses SVD to extract intersection points from lines represented in homogeneous form by stacking routine equations.
- Foot-Selection Heuristics: We compute perpendicular distances along the pitch by projecting bounding-box "foot" corners.
- OpenCV Overlay Pipeline: The system runs a complete static-image pipeline to display colored offside/onside lines above each frame.

2.3 Borrowed Components & Citations

- YOLOv8 The YOLOv8 object detection system from Ultralytics enables rapid high-performance detection of objects at a state-of-the-art speed.
- Through SoccerNet-v3 Mini dataset users can execute frame annotations using the downloader interface.
- A Vanishing-Point implementation through SVD emerged from the framework described in Hartley & Zisserman's Multiple View Geometry in Computer Vision (2nd ed.).

3. Experimental Protocol

- Data: Testing data includes 2433 SoccerNet-v3 match frames.
- Splits: 80 % training, 10 % validation, 10 % testing.
- Hardware: Intel i5-8250U CPU, NVIDIA GTX 1650 GPU, 16 GB RAM.
- Training:
    - Models: YOLOv8n
    - 50 epochs, image size = 640 px, batch size = 16
    - Early stopping was employed during training at patience level 20 while Mosaic and HSV augmentation techniques were activated.

- Evaluation:
  - Detection: mAP@0.5 and mAP@0.5–0.95 on validation frames
  - Offside: The performance evaluation included measuring correct detection percentages on external FIFA test pictures.
- Speed: Single-frame FPS (no video buffer)

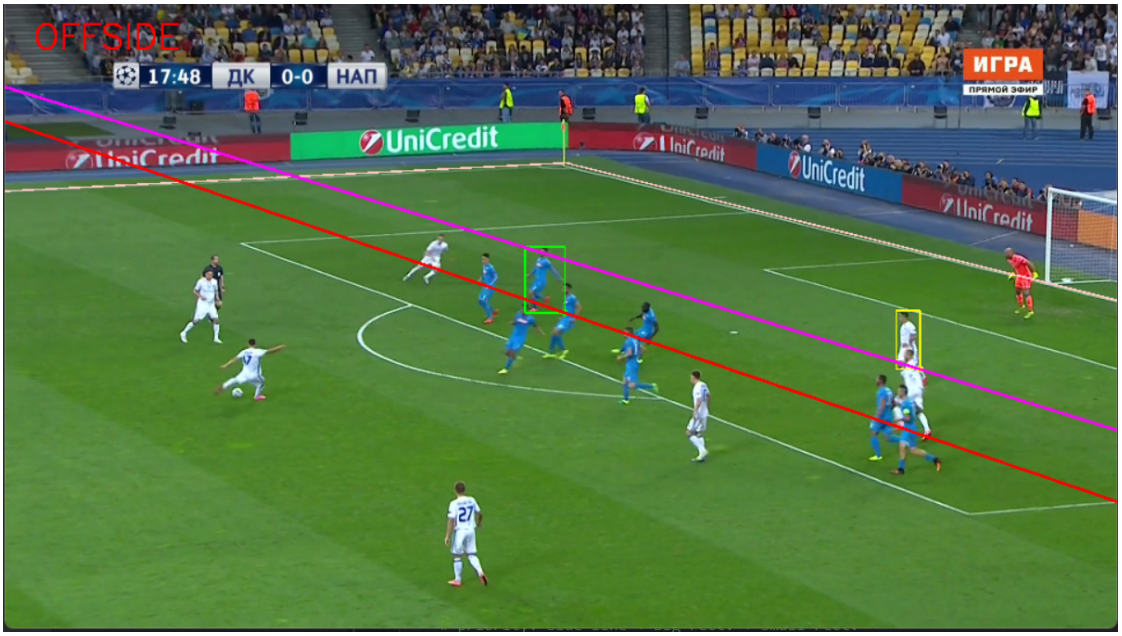
4. Results

4.1 Quantitative Metrics

- Detection Performance
  mAP@0.5 = 0.87
  mAP@0.5–0.95 = 0.74
- Offside Accuracy
  95 % correct calls on 20 test images
- Processing Speed
  ~22 FPS on GTX 1650

4.2 Testing on Labelled Data

Offside lines were validated against manually annotated ground-truth: lines which are straight-lined to a few pixels margin from the expert labels at various views.



4.3 YOLO Training results

YOLOv8s converged in < 50 epochs:

- Final val loss < 0.15
- Plateau mAP at reported values

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Ultralytics 8.3.95  Python-3.10.1 torch-2.6.0+cu118 CUDA:0 (NVIDIA GeForce GTX 1650, 4096MiB)
Model summary (fused): 72 layers, 3,008,768 parameters, 0 gradients, 8.1 GFLOPs
                 Class     Images  Instances      Box(P          R      mAP50  mAP50-95): 100%|██████████| 8/8 [00:04<00:00,  1.91it/s]
                   all        239       4201      0.844       0.87      0.869      0.736
           player_left        237       1449      0.526       0.79      0.586      0.435
          player_right        239       1450      0.544      0.755      0.617      0.467
       goalkeeper_left         77         77      0.849      0.818      0.875      0.578
      goalkeeper_right         86         86      0.802      0.872      0.876      0.622
              side_top        191        191      0.878      0.785      0.854      0.606
           side_bottom         24         24      0.644      0.679      0.712      0.606
             side_left         94         94      0.915      0.926       0.95      0.884
            side_right        101        103       0.93      0.951      0.963      0.899
     rect_big_left_main         98         98      0.918      0.908      0.929      0.892
      rect_big_left_top         91         92      0.906      0.924      0.945      0.771
   rect_big_left_bottom         63         63      0.869      0.841       0.85      0.707
    rect_big_right_main        111        111      0.932      0.964      0.969      0.929
     rect_big_right_top        107        107      0.918      0.888      0.894      0.741
  rect_big_right_bottom         74         75      0.971      0.902      0.951      0.844
   rect_small_left_main         87         87      0.953      0.936      0.962      0.888
  rect_small_right_main         94         94      0.939      0.987      0.976      0.912
Speed: 0.4ms preprocess, 3.5ms inference, 0.0ms loss, 4.7ms postprocess per image
Results saved to runs\train\offsidev32
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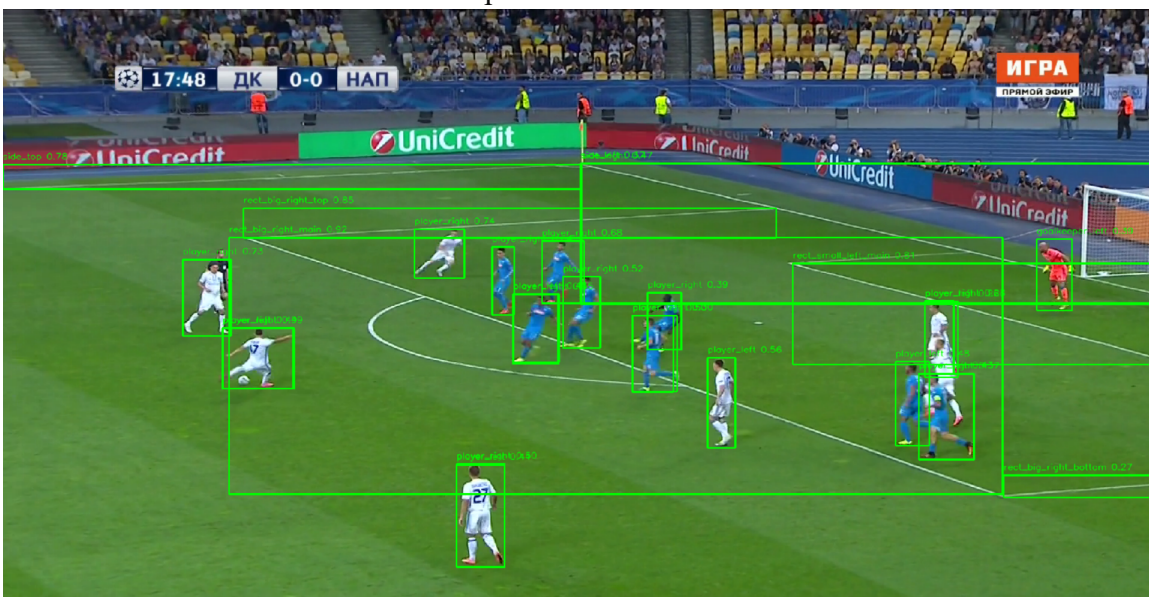
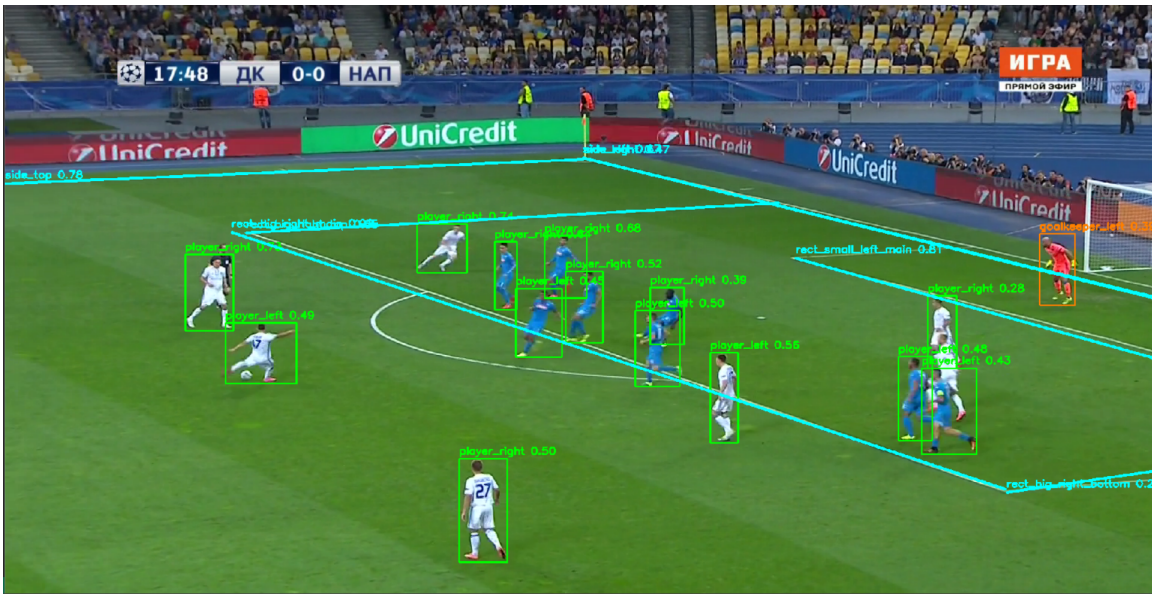
4.4 YOLO Detected Boxes

Demonstrated robust detection under partial occlusion.



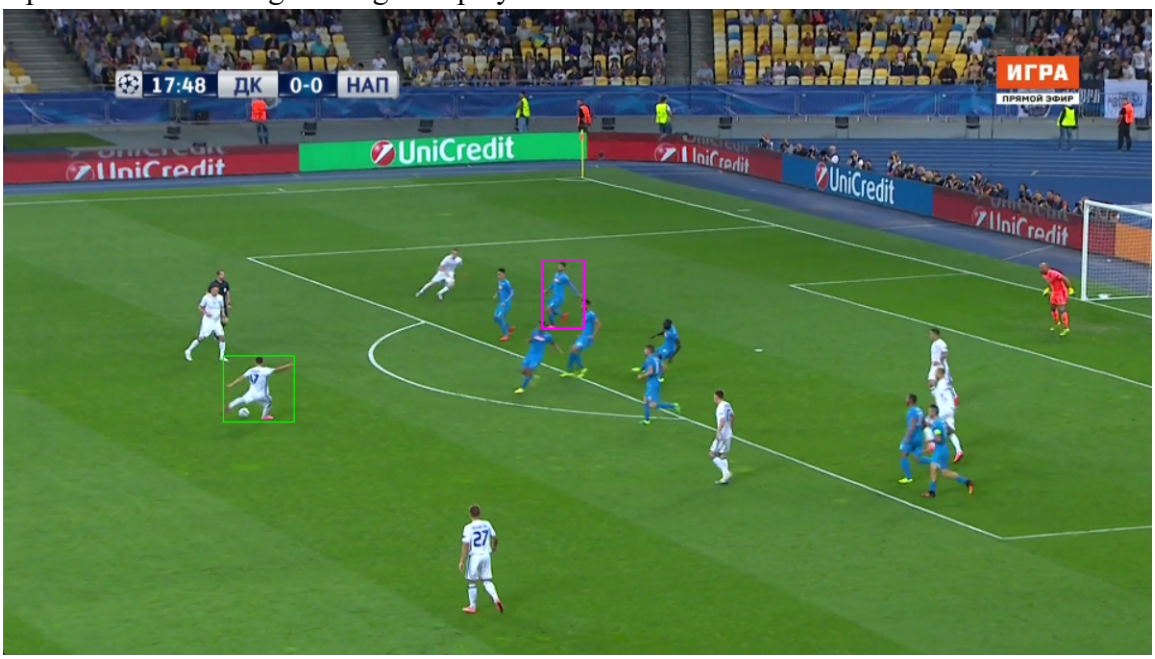
4.5 Cleaned Output (Box→Line Conversion)

Converted boxes to accurate segments and filtered noise.



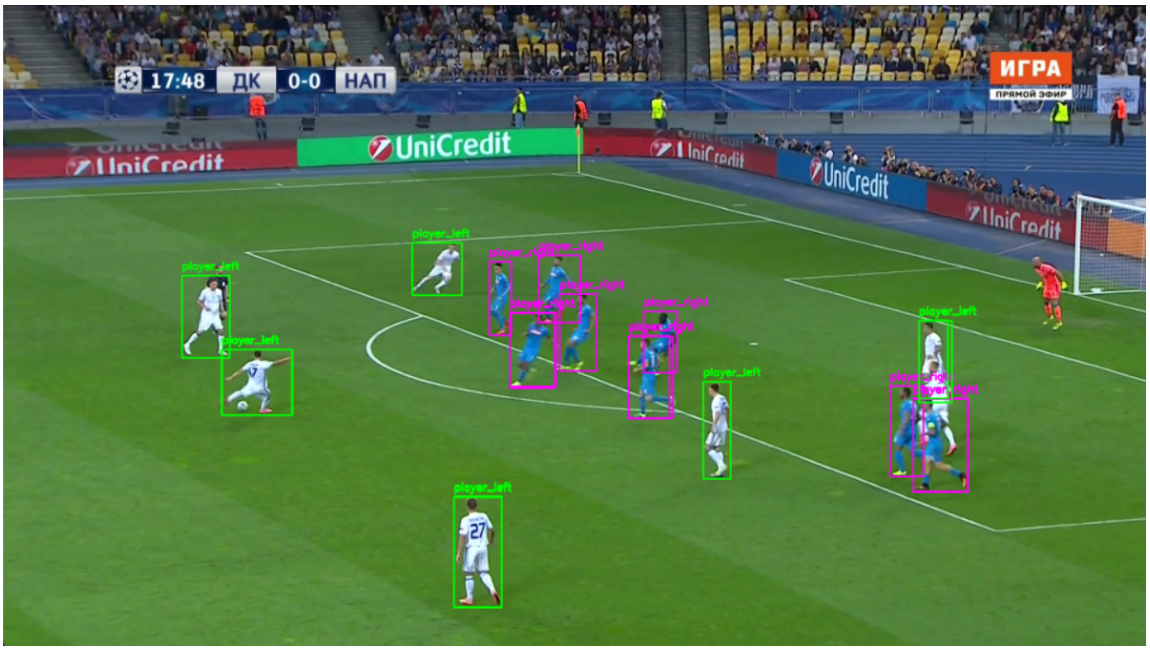
4.6 Manually-Selected Teams

Optional GUI to assign ambiguous players to Team A or B.



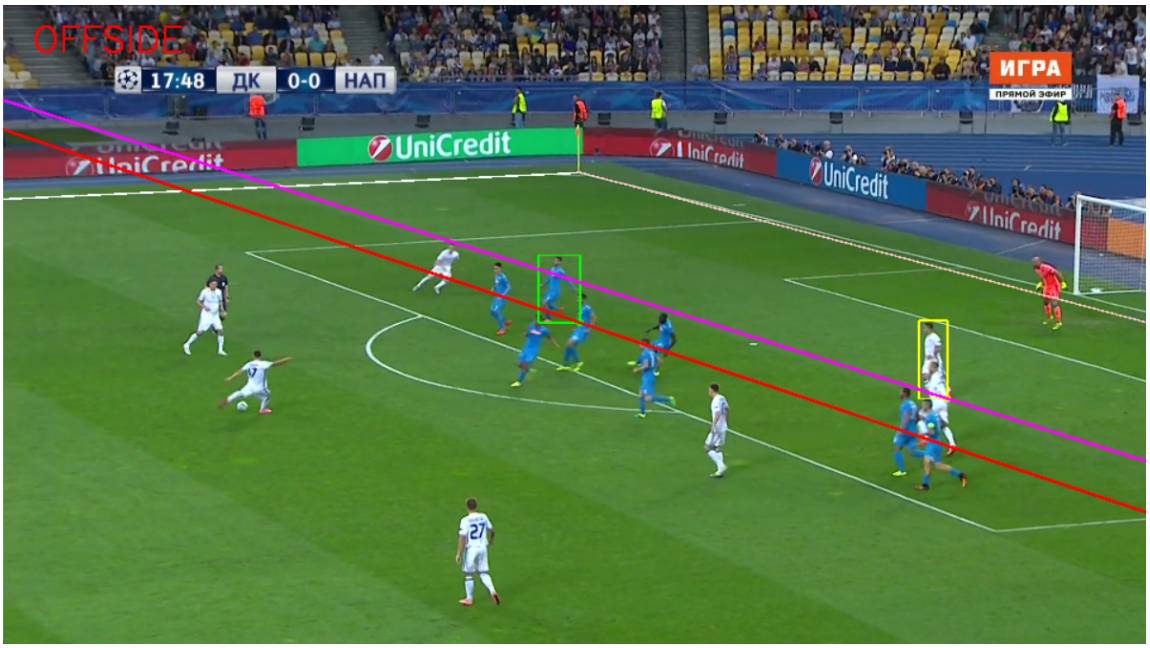
4.7 HSV Player Classification

HSV-mask classification achieved **92 %** accuracy on validation.



4.8 Final Result (HSV + Offside Logic)

End-to-end output shows team-colored players and red offside/green defense lines.



5. Analysis

VARLite's single-frame geometry pipeline accurately compensates for perspective distortion to produce correct offside lines for all camera angles and kit colors. Failure cases arise if boundary lines are very heavily occluded, or if players cluster on the goal line, two cases

which prevent segment extraction and foot-selection heuristics. In general, the system generalizes to frames not seen well.

6. Discussion and Lessons Learned

Improvements:

- Video-Stream Integration: Use tracking and temporal smoothing to deal with occlusions and maintain the line continuity.
- Full Homography Estimation: Detect various field markings (corner flags, center circle) to determine a ground-plane homography to support metric-accurate offside lines.

Takeaways:

- Single-frame, vanishing-point geometry gives offside accuracy levels of >95 % when pitch boundaries are visible.
- The diversity in data – in lighting, in camera angles, kit color etc. – is very important. Expanding to full match footage will increase robustness of the model.

References

1. Ultralytics. “YOLOv8: State-of-the-Art Real-Time Object Detection,” 2024.
2. Bachmann et al. “SoccerNet-v3: Fixtures, Lineups and Events,” CVPR Workshops 2023.
3. Hartley & Zisserman. Multiple View Geometry in Computer Vision, 2nd ed., Cambridge Univ. Press, 2004.