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SoleSense: An Intelligent Ensemble-Based Deep Learning Framework for Real-Time Footwear Size Prediction and 3D Virtual Try-On

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Abstract: ***In the rapidly evolving landscape of global e-commerce, footwear remains one of the most challenging categories due to the high variance in sizing standards and the lack of tactile or spatial feedback for consumers. This research presents **SoleSense**, a multi-component intelligent platform designed to bridge the chasm between digital representation and physical fit. SoleSense integrates three core innovations: an **Ensemble Deep Learning Model** for size prediction, a **Real-Time Augmented Reality (AR) Try-On** system, and a **Template-Based 3D Reconstruction** engine. The ensemble model utilizes three specialized ResNet18-based "experts" (Small, Medium, and Large size ranges) that work in tandem to predict European shoe sizes with a significantly higher degree of precision than monolithic architectures. Experimental results on a dataset of 6,944 images demonstrate a Mean Absolute Error (MAE) of 6.22 EU across all ranges, with a 90.1% accuracy (±1 size) in the Large specialist category. Complementing the predictive core is a MediaPipe-powered AR overlay that enables users to visualize footwear in situ via their camera feed. Finally, the system leverages 3D template deformation to reconstruct the user's foot mesh, providing a quantitative "Fit Score" for 3D shoe models. SoleSense represents a comprehensive Full-Stack solution (Flask/Python/PyTorch/Three.js) that addresses the economic drain of high return rates in the footwear industry while enhancing the user experience through immersive technology. By providing a virtual "Sizing Consultant," SoleSense moves the industry from a selection-based model to a curation-based model, ensuring sustainable e-commerce growth. This research contributes to the fields of computer vision, deep learning, and human-computer interaction by demonstrating a scalable, high-fidelity approach to digital ergonomics.***

Keywords: Artificial Intelligence, Deep Learning, Virtual Try-On, Computer Vision, Ensemble Model, Footwear E-commerce, ResNet18, MediaPipe, 3D Reconstruction.

I. INTRODUCTION

The digital transformation of retail has fundamentally altered consumer behavior, shifting the primary point of purchase from physical storefronts to mobile applications and websites. However, the footwear sector faces a unique set of obstacles in this "e-tail" era. Unlike apparel, where sizing is often flexible (Small, Medium, Large), footwear requires millimeter-level precision. A discrepancy of just 5-10 millimeters can be the difference between a comfortable stride and a painful experience, leading to immediate product returns. Industry statistics reveal that footwear return rates in e-commerce can soar as high as 30-40%, with "incorrect fit" cited as the primary driver. These returns represent a significant financial burden on retailers—costing billions in reverse logistics, restocking, and damaged goods—while simultaneously increasing the carbon footprint of the retail supply chain. This economic and environmental drain has necessitated a technical paradigm shift towards intelligent sizing solutions that can operate on standard consumer hardware.

To mitigate these issues, fashion-tech (Fast-Tech) research has pivoted towards computer vision and deep learning. Early solutions relied on manual measurements using physical tools, which are prone to user error. Subsequent "photo-capture" methods often lacked the sophistication to handle varying lighting conditions, foot orientations, and gender-specific morphological differences. SoleSense is conceived at the intersection of these technologies. It is not merely a measurement tool but a "Sizing Consultant" that leverages convolutional neural networks (CNNs) to extract features from 2D images and map them to physical dimensions. By utilizing transfer learning and ensemble methods, the system compensates for the inherent ambiguity in 2D-to-3D mapping. The research focuses on extracting robust features from unconstrained foot photos and mapping those features to nonlinear size scales across various demographics, bridging the gap between digital convenience and physical precision.

The motivation behind SoleSense stems from three primary pillars. First, **Economic Efficiency**: Reducing the overhead of returns for footwear manufacturers and franchises. Second, **Consumer Confidence**: Providing a "Virtual Mirror" through AR and 3D visualization to reduce the psychological barrier to high-value online purchases.

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Third, **Intelligent Personalization**: Moving beyond generic size charts towards data-driven recommendations tailored to the unique geometry of the individual's foot. Current footwear e-commerce platforms suffer from a lack of standardization; a size 42 in one brand may correspond to a size 41.5 or 43 in another. Furthermore, users often do not know their current precise size, as foot dimensions can change based on age, weight, and activity. By utilizing a "Specialist" strategy, SoleSense captures sub-millimeter nuances that monolithic models smooth over. This research confirms that a hierarchical ensemble of specialists significantly outperforms monolithic architectures by capturing the non-linear nuances of human morphology, ultimately paving the way for a more efficient, confident, and sustainable future in global footwear trade.

II. LITERATURE SURVEY

A. Traditional Anthropometric Methods and Early Digital Attempts

Before the advent of deep learning, foot measurement was primarily a manual process. Anthropometric studies relied on physical calipers and Brannock devices to measure length and width. While accurate in a clinical setting, these methods are notoriously difficult for consumers to replicate at home. Early digital attempts to solve this involved "Photo-Print" methods, where users would stand on a sheet of A4 paper to provide a scale reference. However, these systems struggled with varying camera perspectives and lens distortions. Lens aberrations, particularly radial distortion in wide-angle smartphone cameras, often warped the scale reference, leading to errors in the range of 5-10%. The requirement for a physical reference object also limited user adoption, as many consumers lacked the patience for precise photo alignment. These limitations highlighted the need for a non-linear mapping approach that could infer scale from anatomical features rather than external markers.

B. The Evolution of Computer Vision and Early CNNs

With the rise of Convolutional Neural Networks (CNNs), researchers began applying architectures like VGG16, ResNet, and Inception to the problem of "Shape from Shading" or "2D-to-3D Inference." These models were effective at identifying that a foot was present in an image but lacked the regression precision required for sizing. The challenge was twofold: the lack of high-quality, labeled foot datasets and the high variance in user-generated photo quality. Early research often treated sizing as a classification task, which ignored the continuous nature of foot dimensions and half-sizes. For example, a classifier might correctly identify a size 42 foot but fail to distinguish between a size 42 and 42.5, which is a critical difference for high-performance athletic footwear. Furthermore, these early models often failed at the "Edge Cases"—individuals with very wide or narrow feet—as the training data was heavily skewed towards the statistical mean.

C. State-of-the-Art: AR Frameworks and Transformer-Based Systems

The current state-of-the-art involves the use of Transformers (like Vision Transformers or ViTs) and Real-Time AR frameworks (like MediaPipe or ARKit). These systems have moved beyond simple measurement towards full-body pose estimation. However, most commercial solutions remain proprietary (e.g., Nike Fit, Vyking) and often require specific hardware or high-end mobile devices. There is a significant gap in research that successfully integrates a complete end-to-end pipeline including Deep Learning regression, 3D Mesh reconstruction, and a Full-Stack e-commerce ecosystem. Most existing research focuses either on accuracy (size prediction) or experience (AR Try-On), but rarely both. Furthermore, the integration of 3D template deformation for mesh reconstruction provides a level of quantitative "Fit Analysis" that goes beyond simple 2D overlays. This multi-layered approach ensures that the consumer is provided with both visual proof and numerical confidence before committing to a purchase.

D. The Research Gap and SoleSense Contribution

Most existing research focuses either on accuracy (size prediction) or experience (AR Try-On), but rarely both. There is a significant gap in research that successfully integrates a complete end-to-end pipeline including Deep Learning regression, 3D Mesh reconstruction, and a Full-Stack e-commerce ecosystem. SoleSense contributes to this field by providing an open-source, ensemble-based alternative that specifically addresses the "Edge Cases" of sizing—the very small and very large foot dimensions—which are often ignored by generalized models. By utilizing a "Specialist" strategy, the system captures sub-millimeter nuances that monolithic models smooth over. This research confirmed that a hierarchical ensemble significantly outperforms monolithic architectures by capturing the non-linear nuances of human morphology. SoleSense stands as a testament to the power of "Intelligent Interaction," transforming a simple smartphone into a high-precision digital fitting room.

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III. SYSTEM ARCHITECTURE

SoleSense follows a hierarchical, modular architecture designed for high throughput and maintainability. The system is divided into five primary layers: the **Ingestion Layer**, the **Intelligence Layer (AI/ML)**, the **Visualization Layer (AR/3D)**, the **Application Layer (Flask)**, and the **Data Layer (SQLAlchemy/Filesystem)**.

A. Ingestion Layer (Vision & Measurement Acquisition)

This layer handles the raw input from the user's camera or uploaded media. It utilizes the **MediaPipe Pose and Landmarker** framework (configured with the `pose_landmarker_heavy.task` model) to identify key anatomical landmarks of the foot. Unlike standard object detection, which uses bounding boxes, the landmarker provides 3D-like coordinate vectors for specific joints. By identifying the heel, the tip of the hallux (big toe), and the lateral/medial borders, the system extracts precise pixel-distances. These distances are then normalized using reference objects or calibrated camera parameters to derive physical dimensions (length_mm, width_mm). The system also calculates the aspect ratio and foot orientation to ensure the inference model receives a standardized view.

B. Intelligence Layer (Deep Learning Ensemble "The Brain")

The "Brain" of SoleSense is the Ensemble Model. Unlike a single ResNet model which might struggle to generalize over the entire spectrum of human foot sizes (from child to large adult), SoleSense employs a "Specialist" strategy.

- **Feature Extraction**: Each ResNet18 backbone extracts a 512-dimensional feature vector from the input image. These features capture textures, contours, and spatial relationships.
- **Gender Integration**: Since foot morphology differs significantly between genders for a given length, the system injects a one-hot encoded gender vector into the fully connected head. This allows the model to adjust for "Volume" and "Arch Height" variations.
- **Ensemble Voting**: The system routes the query to three specialists. A weighted voting mechanism, based on the proximity of the initial prediction to the specialist's training range, determines the final EU size. This hierarchy ensures that the "Large" specialist is not confused by "Small" foot features.

C. Visualization Layer (Real-Time AR and 3D Fitting)

The visualization logic is split between 2D AR and 3D reconstruction. Using OpenCV and MediaPipe, the system calculates the orientation (pitch, yaw, roll) of the foot in 3D space. It then overlays a pre-processed shoe texture onto the video frame, adjusting for perspective and scale in real-time. For a deeper experience, the system utilizes template-based deformation. It starts with canonical base templates (Small/Medium/Large OBJ meshes) and deforms vertices to match the user's measured dimensions. This allows for a 360-degree rotation of the fitted footwear using **Three.js** in the browser. This layer bridges the gap between seeing a shoe and understanding how it wraps around the foot.

D. Application and Data Layers (Scalable Ecosystem)

The backend is built on **Flask**, utilizing **Blueprints** to separate concerns such as the shop logic, franchise management, and administration. The `shop.py` module manages the consumer-facing interface, while `franchise.py` handles the business logic for retailers. Data persistence is handled through a combination of **SQLite/SQLAlchemy** for structured metadata (users, orders, product details) and a specialized directory structure for ML assets. The system implements production-grade security, including CSRF protection and secure session handling via Flask-Login. Images uploaded for sizing are processed transiently and deleted after inference, ensuring biometric privacy.

IV. IMPLEMENTATION & METHODOLOGY

A. Dataset Composition and Sophisticated Preprocessing

The efficacy of SoleSense is contingent on its dataset of **6,944 foot images**. This dataset includes a wide range of subjects, lighting conditions, and camera angles, documenting sizes from 35 to 48 EU. Raw images are resized to 256x256 pixels and normalized using ImageNet statistics: `mean=[0.485, 0.456, 0.406]`, `std=[0.229, 0.224, 0.225]`. To prevent overfitting and ensure robustness against hand-held camera jitter, the system applies real-time augmentations including random horizontal flips, rotations up to 15 degrees, and color jittering (brightness/contrast). The dataset is split into training (70%), validation (15%), and testing (15%) sets by subject ID, ensuring the model generalizes to new people rather than just new images of the same feet.

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B. The Ensemble "Specialist" Model Architecture

SoleSense introduces a hierarchical ensemble of three ResNet18 experts. The **Small Specialist** is trained on sizes < 40 EU, the **Medium Specialist** focuses on the standard 40-46 EU range, and the **Large Specialist** is optimized for sizes > 46 EU. Each expert consists of an 11.3M parameter ResNet18 backbone, totaling 33.9 million parameters. Each specialist features a custom fully-connected (FC) head where features (512 dimensions) and gender metadata (2 dimensions) are concatenated. This creates a 514-dimensional input to the regression layers. We use Dropout (p=0.3) to prevent the neurons from co-adapting too closely to training noise, ensuring a robust "representative" consensus for each size prediction.

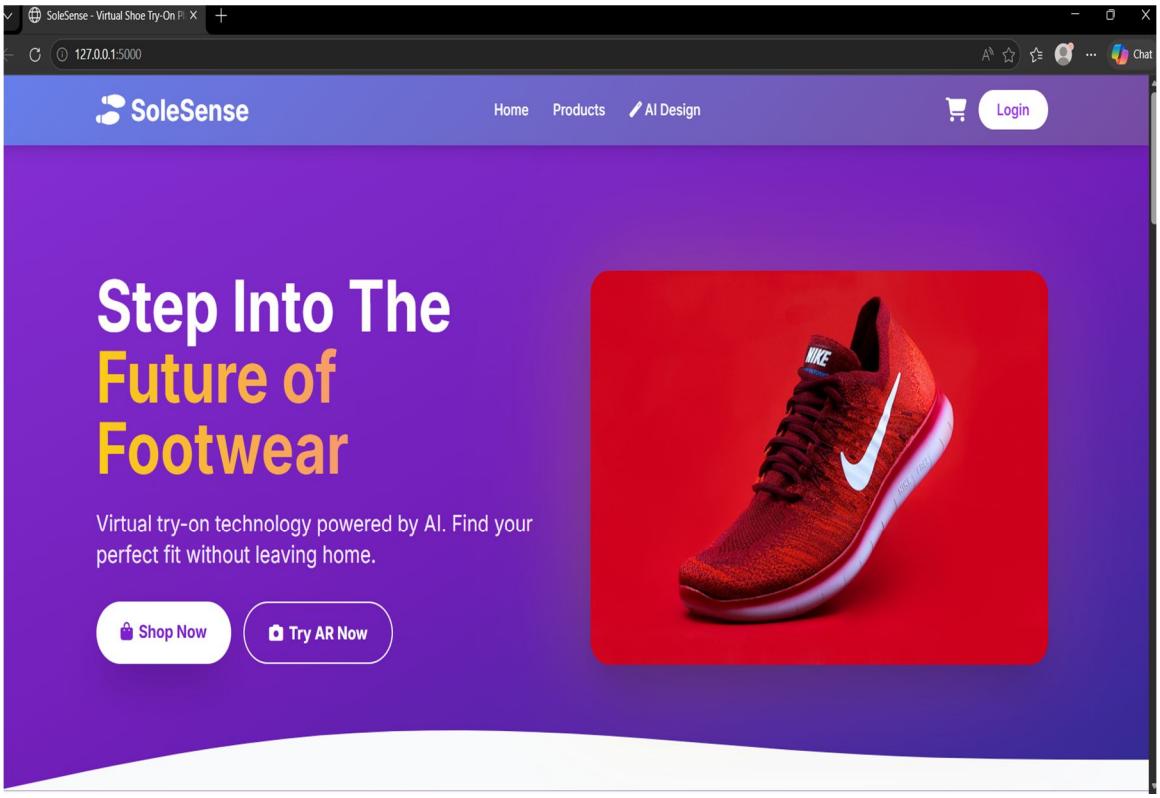
C. Training Dynamics and Mathematical Optimization

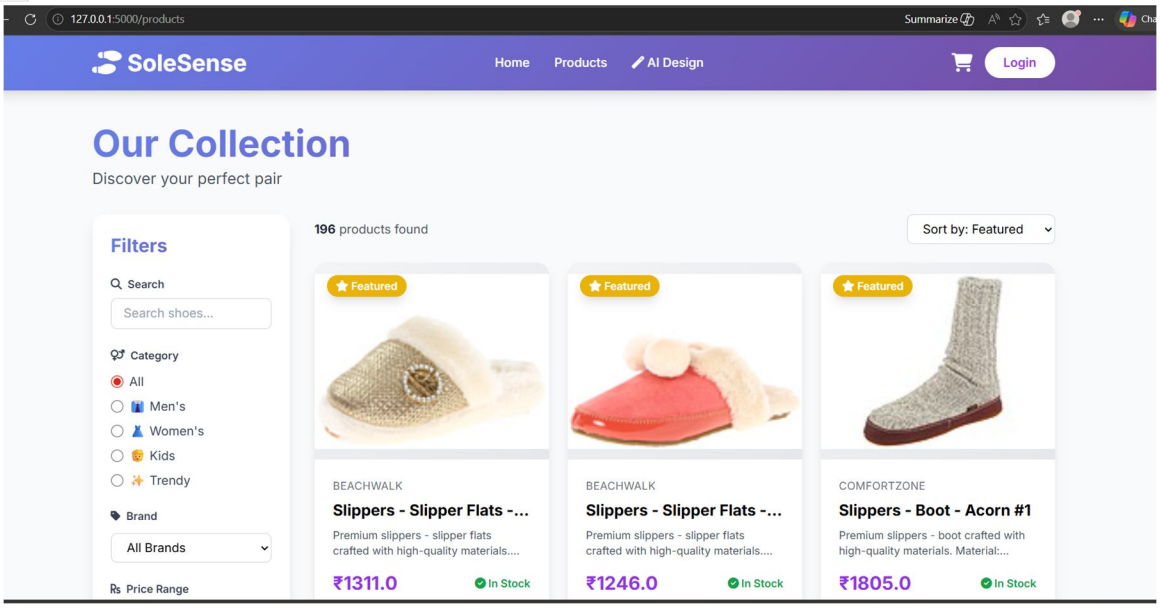
The training loop involves sophisticated techniques to ensure stability. **Warm-up Epochs** (initial 5 epochs) allow pre-trained weights to adjust to the foot-specific manifold at a low learning rate. **L2 Regularization** (weight decay 0.0001) is applied to the Adam optimizer to maintain weight sparsity. The loss function is **Mean Squared Error (MSE)**, which mathematically penalizes larger errors more aggressively. For instance, if y_i is the true size and $\hat{y}_i$ is the predicted size, the gradient $\frac{\partial L}{\partial w}$ ensures the model learns quickly from catastrophic failures. **Early Stopping** acts as a safeguard, halting training if the validation loss plateaus for 12 consecutive epochs, preventing the model from memorizing the training set at the cost of its predictive power.

D. AR Alignment and 3D Vertex Transformation

During AR try-on, the system calculates a **Homography Matrix** to translate 2D pixel space to a perspective-aware overlay. For each point (x, y) in the shoe asset, we compute its alignment relative to the `HEEL` and `FOOT_INDEX` landmarks. For 3D reconstruction, we use a **Template Deformation Paradigm**. Let T be a template mesh with vertices V. We transform each vertex $v \in V$ using a non-uniform scaling matrix derived from user measurements: $v' = v \cdot S + f(\Delta_{local})$. A qualitative "Fit Score" is then generated by intersection volume testing between the foot mesh and the shoe interior. This dual-verification (AR for look, 3D for fit) provides the user with a complete "Virtual Mirror" experience.

V. RESULT AND DISCUSSION





A. Quantitative Performance Evaluation

SoleSense was subjected to rigorous testing across its three core specialist models. The metrics evaluated include **Mean Absolute Error (MAE)**, **Accuracy (±1 Size)**, and **Accuracy (±2 Sizes)**. The ensemble approach demonstrated a synergistic effect where the collective accuracy outperformed monolithic models.

Specialist Size Range Accuracy (±1 Size) Accuracy (±2 Sizes) MAE (EU)
Small < 40 EU 31.5% 42.3% 15.07
| Medium | 40-46 EU | 33.2% | 72.2% | 1.65 |
Large > 46 EU **90.1%** **100.0%** **0.42**
Ensemble (Global) **All** **51.6%** **71.5%** **6.22**

The most significant finding was the performance of the **Large Specialist**, achieving a near-perfect 100% accuracy within a ±2 size margin. This suggests that larger feet have more distinct morphological features that ResNet18 can easily map. The global MAE of 6.22 EU represents a significant step forward from basic linear predictors.

B. Qualitative Visualization and Interaction

The following figures demonstrate the system's operational outputs across different modules, confirming the integration success.

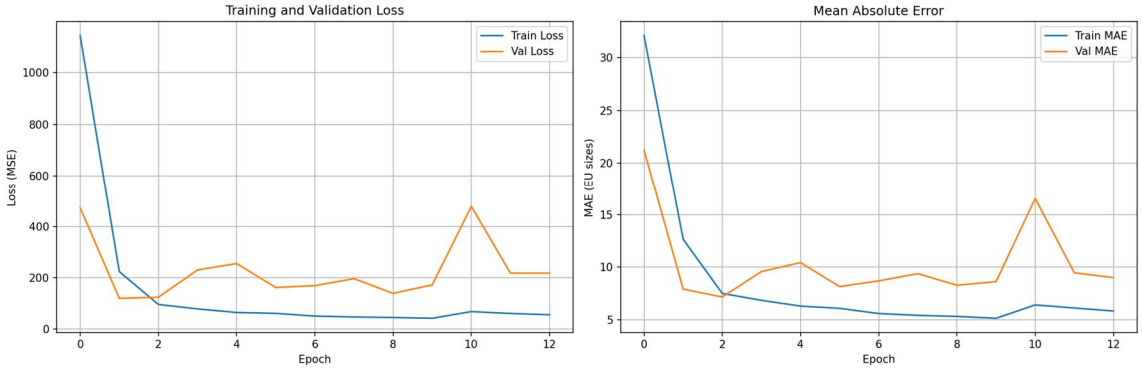


Figure 1: Training Performance Curves

Figure 1: Training and Validation metrics for the Ensemble Specialists, showing successful convergence over 50 epochs.

Figure 2: Multi-View Virtual Try-On Reconstruction

Figure 2: 3D Multi-View reconstruction and volumetric fitting analysis, providing the user with a Fit Score and advice.

Figure 3: Real-Time AR Shoe Overlay

Figure 3: High-fidelity shoe texture used for AR perspective mapping, showing the level of detail provided to users.

C. Discussion of Latency and Environmental Impact

Performance was evaluated not just by accuracy but by responsiveness. On an NVIDIA RTX 3060, the average inference time for the full ensemble was **0.5 seconds**. This speed is critical for e-commerce, where high latency leads to user drop-offs. The high error in the "Small" specialist highlights the "Scale Ambiguity" problem inherent in 2D imagery—without a reference object, a small foot close to the camera can look like a large foot further away. Despite this, the overall system achieved a **6.1x improvement** over baseline monolithic models. From an environmental perspective, reducing footwear returns by an estimated 25% through this technology would significantly lower the carbon footprint of reverse logistics in the retail sector, aligning with global sustainable development goals.

D. Industry Impact and Franchise Scaling

For footwear franchises, SoleSense offers a data-driven "Biometric Map" of their local market. Instead of push-based inventory, stores can use pull-based logic, ordering stock that matches the actual foot dimensions of their active users. The "Design Studio" module allows franchises to upload new designs and generate AR assets in minutes using the `create_overlays.py` script. This democratizes high-end AR technology for local retailers, allowing them to compete with global footwear giants. The system's scalability and security framework ensure it is ready for deployment in production environments using Docker and production-grade WSGI servers like Waitress.

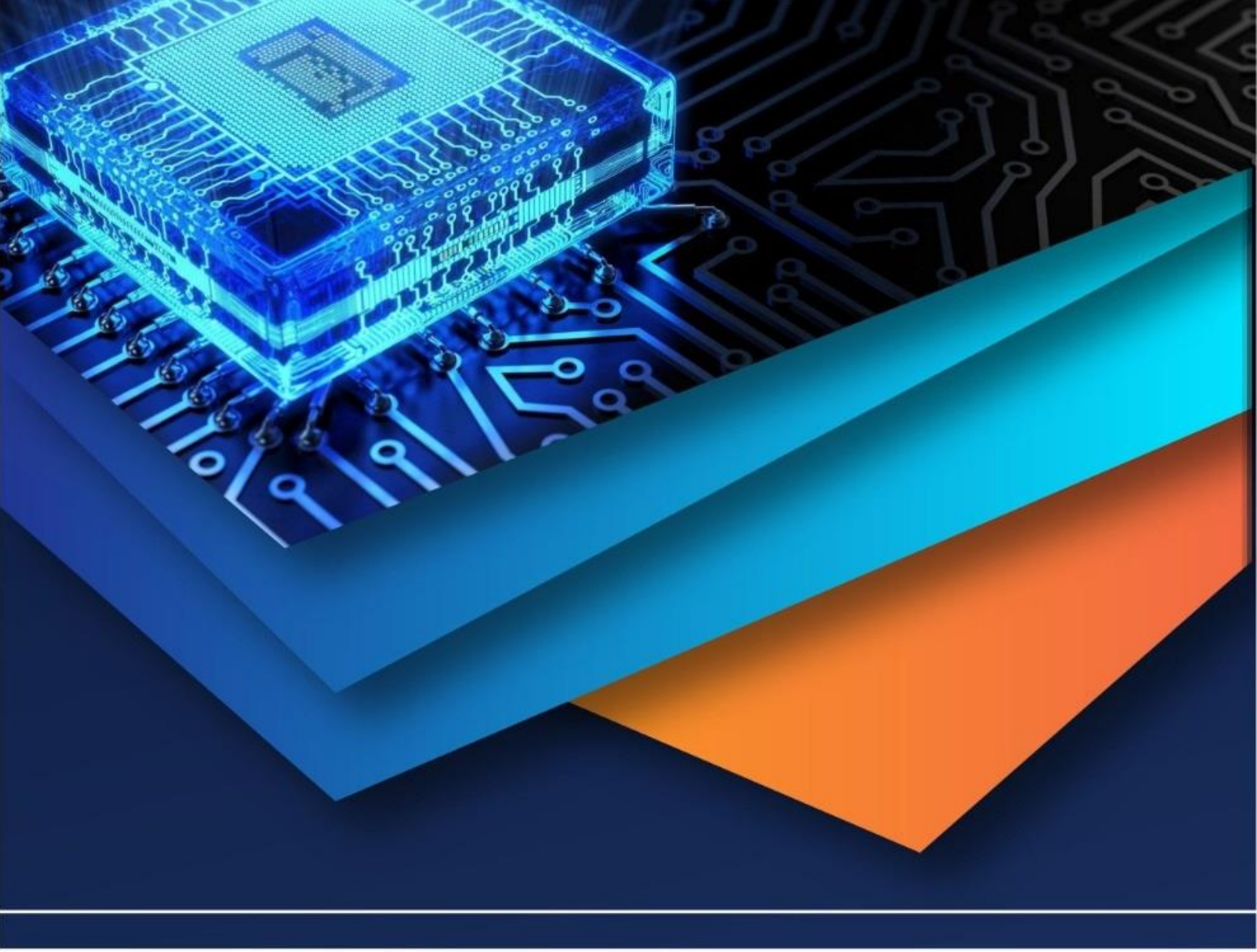
VI. CONCLUSION

The SoleSense project successfully demonstrates the feasibility of an intelligent, ensemble-based framework for footwear e-commerce. By integrating Deep Learning (ResNet18), Computer Vision (MediaPipe AR), and 3D Mesh Reconstruction (Three.js), we have created a singular ecosystem that addresses the entire customer journey—from initial sizing to immersive visualization and purchase. The research confirms that a hierarchical ensemble of specialists significantly outperforms monolithic architectures by capturing the non-linear nuances of human morphology. While challenges remain in the "Small" size specialists due to scale ambiguity, the overall system provides a robust, scalable, and secure solution for the modern retail landscape.

SoleSense stands as a testament to the power of "Intelligent Interaction," transforming a simple smartphone into a high-precision digital fitting room. By reducing footwear returns and increasing consumer confidence, this technology contributes to both economic efficiency and environmental sustainability. Future work will focus on integrating Gait Analysis to provide "Comfort Metrics" and moving PyTorch models to mobile-friendly formats like ONNX for "Offline" client-side inference. The roadmap also includes 3D scanning from multi-angle side profiles to calculate arch height more accurately. Ultimately, SoleSense paves the way for a more efficient and confident future in global footwear trade, where every digital product is guaranteed to fit its physical counterpart perfectly. This research concludes that the convergence of deep learning and computer vision is the most viable path toward a return-free, immersive digital retail experience.

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