RAILS — Überwachtes CNN-Training für Schienenuntergrund-Klassifikation

Ziel: Training und Evaluation eines überwachten CNN (Transfer Learning mit ResNet50V2) zur präzisen Klassifikation von Eisenbahn-Gleisbettbildern. Aufbauend auf der unüberwachten Clustering-Analyse implementiert dieses Notebook eine **vollständige, eigenständige ML-Pipeline**:

1. **Daten-I/O** aus TFRecord-Format (Parsing, Dekodierung, Normalisierung)
2. **Modelldefinition** (vortrainiertes ResNet50V2-Backbone + leichter Klassifikationskopf)
3. **Training** mit der *besten Konfiguration* (siehe unten)
4. **Evaluation** mit detaillierten Metriken (Confusion Matrix, klassenweise Precision/Recall/F1, Macro/Weighted Scores)
5. **Visualisierung** (Trainingskurven, Confusion Matrix, klassenweise Balkendiagramme, Klassenverteilung)
6. **Artefakte** (gespeichertes Modell + CSV/JSON-Ergebnisse)

Das Notebook basiert auf den Erkenntnissen der vorhergehenden Clustering-Phase und nutzt die beste, durch systematische Hyperparameter-Optimierung ermittelte Konfiguration für das finale Training.

Schnellstart & Konfiguration

Was:

- Setzt die Pfade zu den **TFRecord**-Dateien für Training und Evaluation.
- Definiert **Ausgabeverzeichnis** und **Modellnamen** für Trainingsartefakte.
- Legt **Klassenliste** und **Bildabmessungen** (224×224×3) fest, passend zum verwendeten Backbone.
- Bündelt die feste **Best-Configuration** (Lernrate, Batchgröße, Epochen, Val-Anteil, Early-Stopping-Patience).

Warum:

- Zentrale Konfiguration ermöglicht **reproduzierbare** Läufe ohne Parameter-Sweeps.
- TFRecords als einheitliches Eingabeformat erleichtern **schnelles Laden** via `tf.data`.
- Feste Hyperparameter sichern **Vergleichbarkeit** und verhindern „Experiment Creep".
- Ein Val-Anteil und Early Stopping unterstützen **stabiles Trainieren** und vermeiden Über-/Unteranpassung.

```
# TFRecord inputs
# possible datasets: MultiLabel_TB_small_08-25.tfrecord, MultiLabel_TB_medium_08-25.tfrecord, MultiLabel_TB_large_08-25.tfrecord)
TRAIN_TFRECORD_PATH = "/media/andi/ssd2/dev/code/Overseer2/data/inputs/MultiLabel_TB_large_08-25.tfrecord"
EVAL_TFRECORD_PATH  = "/media/andi/ssd2/dev/code/Overseer2/data/inputs/MultiLabel_TB_Evaluation_08-25.tfrecord"

# Output directory + model name
OUTPUT_DIR = "./outputs_trackbed"
# possible arichtectures in ./architectures
MODEL_NAME = "PT_MultiClassResNet50_Trackbed"

# Label mapping and image shape (matches our ResNet50V2 setup)
CLASSES = ["ASPHALT", "BALLAST", "GRAS", "STONE", "ERROR"]
NUM_CLASSES = len(CLASSES)
IMG_HEIGHT = 224
IMG_WIDTH  = 224
IMG_DEPTH  = 3

# stardard training configuration (used for all trainings)
BEST_CONFIG = {
    "learning_rate": 1e-4,
    "batch_size": 32,
    "num_epochs": 30,
    "val_fraction": 0.2,         # reserve a small fraction of TRAIN for validation
    "early_stopping_patience": 5 # be gentle to avoid over/under-fitting
}
```

1. Setup: Umgebung & Reproduzierbarkeit

Was:

- Initialisierung von TensorFlow und Import der erforderlichen Bibliotheken
- Setzen von Seeds für Determinismus (soweit auf GPU praktikabel)
- Aktivierung des GPU-Memory-Growth zur Vermeidung von OOM-Fehlern

Warum:

- **Reproduzierbarkeit:** Konsistente Ergebnisse über mehrere Trainingsläufe hinweg
- **GPU-Optimierung:** Effiziente Speichernutzung verhindert Speicherüberläufe
- **Zentralisierte Konfiguration:** Alle Seeds und Umgebungseinstellungen an einem Ort

Outputs:

- Konfigurierte TensorFlow-Umgebung mit aktiviertem Memory-Growth
- Erstellung des Output-Verzeichnisses für Modell-Artefakte
- Ausgabe der TensorFlow-Version und des absoluten Output-Pfads

```python
import os, json, random, math, itertools
from pathlib import Path
from datetime import datetime

import numpy as np
import tensorflow as tf

# Reproducibility (best-effort on GPU)
SEED = 123
os.environ["PYTHONHASHSEED"] = str(SEED)
tf.random.set_seed(SEED)
np.random.seed(SEED)
random.seed(SEED)

# GPU memory growth (optional but recommended)
gpus = tf.config.experimental.list_physical_devices('GPU')
if gpus:
    try:
        for gpu in gpus:
            tf.config.experimental.set_memory_growth(gpu, True)
        print(f"Enabled memory growth for {len(gpus)} GPU(s).")
    except Exception as e:
        print(f"Could not set memory growth: {e}")

# Create output dir
Path(OUTPUT_DIR).mkdir(parents=True, exist_ok=True)

print("TF version:", tf.__version__)
print("Output dir:", os.path.abspath(OUTPUT_DIR))
```

```
2025-09-07 15:30:27.291229: E
external/local_xla/xla/stream_executor/cuda/cuda_fft.cc:485] Unable to
register cuFFT factory: Attempting to register factory for plugin
cuFFT when one has already been registered
2025-09-07 15:30:27.370952: E
external/local_xla/xla/stream_executor/cuda/cuda_dnn.cc:8454] Unable
to register cuDNN factory: Attempting to register factory for plugin
cuDNN when one has already been registered
2025-09-07 15:30:27.391148: E
external/local_xla/xla/stream_executor/cuda/cuda_blas.cc:1452] Unable
to register cuBLAS factory: Attempting to register factory for plugin
cuBLAS when one has already been registered
2025-09-07 15:30:27.493806: I
tensorflow/core/platform/cpu_feature_guard.cc:210] This TensorFlow
binary is optimized to use available CPU instructions in performance-
critical operations.
```

```
To enable the following instructions: AVX2 FMA, in other operations,
rebuild TensorFlow with the appropriate compiler flags.
2025-09-07 15:30:28.763974: W
tensorflow/compiler/tf2tensorrt/utils/py_utils.cc:38] TF-TRT Warning:
Could not find TensorRT

Enabled memory growth for 1 GPU(s).
TF version: 2.17.1
Output dir: /media/andi/ssd2/dev/code/RAILS/outputs_trackbed

WARNING: All log messages before absl::InitializeLog() is called are
written to STDERR
I0000 00:00:1757251831.288683    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
I0000 00:00:1757251831.425796    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
I0000 00:00:1757251831.431189    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
```

2. Daten-Pipeline: TFRecord → `tf.data.Dataset`

Was:

- Implementierung der Daten-Pipeline mit dem Schema aus `create_trackbed_tfrecord.ipynb`
- Mehrstufige Verarbeitung: Parsing, Dekodierung, Normalisierung und Batching

Verarbeitungsschritte:

1. **Feature-Parsing** aus jedem TFRecord-Beispiel
2. **Dekodierung** Raw Bytes → Bildtensor; Sicherstellung 3 Kanäle; **Resize auf 224×224**
3. **One-Hot-Encoding** der Labels (5 Klassen)
4. **Normalisierung** auf `[0,1]`-Bereich
5. **Shuffle + Split** von `TRAIN` in **Train/Validation** (nach `val_fraction`) Der `EVAL` TFRecord wird unverändert für die finale Evaluation geladen

Warum:

- **Konsistenz:** Identisches Schema wie bei der TFRecord-Erstellung gewährleistet fehlerfreie Datenverarbeitung
- **Effizienz:** `tf.data.AUTOTUNE` und Prefetching optimieren die Datenlade-Performance
- **Flexibilität:** Separate Funktionen für Training (mit Shuffling) und Evaluation (deterministisch)

Besonderheiten:

- Automatische Grayscale→RGB-Konvertierung für Kompatibilität mit vortrainierten Modellen
- Deterministische Train/Val-Aufteilung durch `take/skip` (reproduzierbar bei unveränderter Dateireihenfolge)
- Rückgabe von Dateinamen bei Evaluation für detaillierte Fehleranalyse

```python
# Feature schema (must match TFRecord writer)
FEATURE_DESC = {
    'image_filename': tf.io.FixedLenFeature([], tf.string),
    'image_raw':      tf.io.FixedLenFeature([], tf.string),
    'height':         tf.io.FixedLenFeature([], tf.int64),
    'width':          tf.io.FixedLenFeature([], tf.int64),
    'depth':          tf.io.FixedLenFeature([], tf.int64),
    'label':          tf.io.FixedLenFeature([], tf.int64),
    'class_name':     tf.io.FixedLenFeature([], tf.string),
}

def _parse_tfrecord(proto):
    """Parse a single Example proto."""
    return tf.io.parse_single_example(proto, FEATURE_DESC)

def _decode_and_preprocess(feat_dict):
    """Decode bytes → image; enforce 3 channels; resize to 224x224;
one-hot label."""
    img = tf.io.decode_raw(feat_dict['image_raw'], tf.uint8)
    h   = tf.cast(feat_dict['height'], tf.int32)
    w   = tf.cast(feat_dict['width'],  tf.int32)
    d   = tf.cast(feat_dict['depth'],  tf.int32)
    img = tf.reshape(img, [h, w, d])

    # If single-channel, convert to RGB for pretrained models
    def to_rgb(x):
        return tf.image.grayscale_to_rgb(x)

    img = tf.cond(tf.equal(d, 1), lambda: to_rgb(img), lambda: img)

    # Resize to model input
    img = tf.image.resize(img, [IMG_HEIGHT, IMG_WIDTH])
    img = tf.cast(img, tf.float32) / 255.0  # normalize

    label_index = tf.cast(feat_dict['label'], tf.int32)
    label_1h    = tf.one_hot(label_index, depth=NUM_CLASSES)
    return img, label_1h

def _decode_with_filename(feat_dict):
    """Variant that also returns the original filename for
evaluation/analysis."""
    img, label_1h = _decode_and_preprocess(feat_dict)
    return img, label_1h, feat_dict['image_filename']

def _count_records(tfrecord_path):
    """Count number of examples in a single-file TFRecord."""
    return sum(1 for _ in tf.data.TFRecordDataset(tfrecord_path))

def load_train_val_ds(tfrecord_path, batch_size, val_fraction=0.1,
shuffle_multiplier=20):
    """Create train/val datasets from a single TFRecord file by a
deterministic split."""
    n_total = _count_records(tfrecord_path)
    n_val   = max(1, int(round(n_total * float(val_fraction))))
    n_train = max(1, n_total - n_val)
    print(f"Found {n_total} samples → train: {n_train}, val: {n_val}")

    raw = tf.data.TFRecordDataset(tfrecord_path)
    raw = raw.map(_parse_tfrecord,
num_parallel_calls=tf.data.AUTOTUNE)

    # We perform a simple split by 'take/skip' (repeatable as long as
the file order doesn't change).
    # For stronger randomness across epochs, you could shuffle before
splitting,
    # but then report the exact split seed in your paper.
    train_raw = raw.take(n_train)
    val_raw   = raw.skip(n_train)

    # Build train ds
    train_ds = (train_raw
                .shuffle(buffer_size=batch_size*shuffle_multiplier,
seed=SEED, reshuffle_each_iteration=True)
                .map(_decode_and_preprocess,
num_parallel_calls=tf.data.AUTOTUNE)
                .batch(batch_size)
                .prefetch(tf.data.AUTOTUNE))

    # Build val ds
    val_ds = (val_raw
              .map(_decode_and_preprocess,
num_parallel_calls=tf.data.AUTOTUNE)
              .batch(batch_size)
              .prefetch(tf.data.AUTOTUNE))
    return train_ds, val_ds, n_train, n_val

def load_eval_ds(tfrecord_path, batch_size):
    raw = tf.data.TFRecordDataset(tfrecord_path)
    raw = raw.map(_parse_tfrecord,
num_parallel_calls=tf.data.AUTOTUNE)
    ds  = (raw
           .map(_decode_with_filename,
num_parallel_calls=tf.data.AUTOTUNE)
           .batch(batch_size)
           .prefetch(tf.data.AUTOTUNE))
    return ds
```

3. Modellarchitektur: ResNet50V2 + Klassifikationskopf

Was:

- Wiederverwendung der bewährten Architektur aus vorhergehenden Experimenten (vgl. Report)
- **ResNet50V2** (ImageNet vortrainiert, eingefroren) + leichter MLP-Klassifikationskopf
- Loss-Funktion: **Categorical Cross-Entropy** (Single-Label, 5-Wege-Softmax)

Warum:

- **Transfer Learning:** Vortrainierte Features von ImageNet bieten robuste Basis für Bildklassifikation
- **Eingefrorenes Backbone:** Verhindert Overfitting bei begrenzten Trainingsdaten und reduziert Trainingszeit
- **Kategoriale Accuracy:** Passende Metrik für Multi-Class Single-Label-Klassifikation

Architektur-Details:

- **Input:** 224×224×3 (RGB-Bilder)
- **Backbone:** ResNet50V2 mit Global Average Pooling
- **Classifier:** Flatten → Dropout(0.3) → Dense(64) → Dense(32) → Dense(16) → Dense(5, softmax)
- **Optimizer:** Adam mit exponentieller Learning Rate Decay (initial_lr=1e-4, decay_rate=0.9)

Outputs:

- Kompiliertes Keras-Modell mit konfigurierten Optimizer und Metriken
- Modell-Summary zur Architektur-Verifikation

```
from tensorflow.keras import Model, Input
from tensorflow.keras.layers import Flatten, Dense, Dropout
from tensorflow.keras.optimizers import Adam
from tensorflow.keras.applications import ResNet50V2
```

```
def build_pt_multilabel_resnets_trackbed(initial_lr=1e-4,
loss_fn='categorical_crossentropy'):
    # Input
    inp = Input(shape=(IMG_HEIGHT, IMG_WIDTH, IMG_DEPTH))

    # Pretrained backbone (frozen)
    base = ResNet50V2(include_top=False, weights='imagenet',
input_shape=(IMG_HEIGHT, IMG_WIDTH, IMG_DEPTH), pooling='avg')
    base.trainable = False

    x = base(inp)
    x = Flatten()(x)
    x = Dropout(0.3)(x)
    x = Dense(64, activation='relu')(x)
    x = Dense(32, activation='relu')(x)
    x = Dense(16, activation='relu')(x)
    out = Dense(NUM_CLASSES, activation='softmax')(x)

    model = Model(inputs=inp, outputs=out)

    # Exponential decay on LR (as in our reference)
    lr_sched = tf.keras.optimizers.schedules.ExponentialDecay(
        initial_learning_rate=float(initial_lr),
        decay_steps=10_000,
        decay_rate=0.9
    )

    opt = Adam(learning_rate=lr_sched)
    model.compile(optimizer=opt, loss=loss_fn,
metrics=[tf.keras.metrics.CategoricalAccuracy(name='categorical_accura
cy')])
    return model

model =
build_pt_multilabel_resnets_trackbed(initial_lr=BEST_CONFIG["learning_
rate"], loss_fn='categorical_crossentropy')
model.summary()
```

```
I0000 00:00:1757251831.493623    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
I0000 00:00:1757251831.497989    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
```

```
I0000 00:00:1757251831.500630    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
I0000 00:00:1757251831.655797    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
I0000 00:00:1757251831.657597    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
I0000 00:00:1757251831.659407    6258 cuda_executor.cc:1015]
successful NUMA node read from SysFS had negative value (-1), but
there must be at least one NUMA node, so returning NUMA node zero. See
more at
https://github.com/torvalds/linux/blob/v6.0/Documentation/ABI/testing/
sysfs-bus-pci#L344-L355
2025-09-07 15:30:31.662123: I
tensorflow/core/common_runtime/gpu/gpu_device.cc:2021] Created
device /job:localhost/replica:0/task:0/device:GPU:0 with 5279 MB
memory:  -> device: 0, name: NVIDIA GeForce RTX 3070 Laptop GPU, pci
bus id: 0000:01:00.0, compute capability: 8.6

Model: "functional"

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━━━━━┓
┃ Layer (type)                    ┃ Output Shape           ┃
Param # ┃
┡━━━━━━━━━━━━━━━━━━━━━━━━━━━━━━━━━╇━━━━━━━━━━━━━━━━━━━━━━━━╇━━━━━━━━━━
━━━━━┩
│ input_layer (InputLayer)        │ (None, 224, 224, 3)    │
0 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
│ resnet50v2 (Functional)         │ (None, 2048)           │
23,564,800 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
│ flatten (Flatten)               │ (None, 2048)           │
0 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
```

```
│ dropout (Dropout)               │ (None, 2048)           │
0 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
│ dense (Dense)                   │ (None, 64)             │
131,136 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
│ dense_1 (Dense)                 │ (None, 32)             │
2,080 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
│ dense_2 (Dense)                 │ (None, 16)             │
528 │
├─────────────────────────────────┼────────────────────────┼──────────
─────┤
│ dense_3 (Dense)                 │ (None, 5)              │
85 │
└─────────────────────────────────┴────────────────────────┴──────────
─────┘

 Total params: 23,698,629 (90.40 MB)

 Trainable params: 133,829 (522.77 KB)

 Non-trainable params: 23,564,800 (89.89 MB)
```

4. Training: Beste Konfiguration (Single Run)

Was:

- Training **ausschließlich** mit der zuvor als optimal identifizierten Konfiguration: `learning_rate=1e-4`, `batch_size=32`, `num_epochs=30`
- Reservation von `val_fraction` (Standard 20%) des Trainingsdatensatzes für Validation

Warum:

- **Fokussierte Analyse:** Konzentration auf die beste Konfiguration statt erneuter Hyperparameter-Suche
- **Effizienz:** Direktes Training mit bewährten Parametern spart Rechenzeit
- **Vergleichbarkeit:** Konsistente Basis für Evaluation und Dokumentation

Callbacks & Monitoring:

- **ModelCheckpoint:** Speichert bestes Modell basierend auf `val_loss`
    - *Warum sinnvoll?*
        - `val_loss` ist die optimierte Zielgröße und reagiert sensitiver als Accuracy.

        - `save_best_only=True` verhindert Modell-Wildwuchs und hält genau **ein** bestes Artefakt bereit.
        - Garantiert ein reproduzierbares Referenzmodell für Auswertung/Deployment.
- **EarlyStopping:** Verhindert Overfitting mit konfigurierbarer Patience (Standard: 6 Epochen)
    - *Warum sinnvoll?*
        - Bricht stagnierende Läufe früh ab → spart Rechenzeit/Ressourcen.
        - `restore_best_weights=True` stellt direkt den besten Gewichtsstand für die Auswertung bereit.
- **CSVLogger:** Persistiert Trainingsmetriken für spätere Analyse

Outputs:

- Trainiertes Modell gespeichert als `.keras`-Datei
- Training-Logs als CSV mit Verlauf von Loss und Accuracy
- Konfigurationsdateien (JSON) für Reproduzierbarkeit
- Konsolen-Ausgabe der finalen Pfade und Datensatzgrößen

```
from tensorflow.keras.callbacks import ModelCheckpoint, EarlyStopping,
CSVLogger

BATCH_SIZE = int(BEST_CONFIG["batch_size"])
EPOCHS     = int(BEST_CONFIG["num_epochs"])
VAL_FRAC   = float(BEST_CONFIG["val_fraction"])

# Load datasets
train_ds, val_ds, n_train, n_val =
load_train_val_ds(TRAIN_TFRECORD_PATH, batch_size=BATCH_SIZE,
val_fraction=VAL_FRAC)
eval_ds = load_eval_ds(EVAL_TFRECORD_PATH, batch_size=BATCH_SIZE)

# Callbacks & paths
timestamp   = datetime.now().strftime("%Y%m%d-%H%M%S")
run_dir     = Path(OUTPUT_DIR) / f"{MODEL_NAME}__{timestamp}"
run_dir.mkdir(parents=True, exist_ok=True)

MODEL_PATH  = str(run_dir / f"{MODEL_NAME}.keras")
LOG_CSV     = str(run_dir / "training_log.csv")
CFG_JSON    = str(run_dir / "config.json")
CLASSES_JSON= str(run_dir / "classes.json")

# Save config & classes for reproducibility
with open(CFG_JSON, "w") as f:
    json.dump(BEST_CONFIG, f, indent=2)
with open(CLASSES_JSON, "w") as f:
    json.dump(CLASSES, f, indent=2)

cbs = [
    ModelCheckpoint(MODEL_PATH, monitor='val_loss',
save_best_only=True, save_weights_only=False, verbose=1),
    EarlyStopping(monitor='val_loss',
patience=int(BEST_CONFIG["early_stopping_patience"]),
restore_best_weights=True, verbose=1),
    CSVLogger(LOG_CSV) #eig raus
]

history = model.fit(
    train_ds,
    validation_data=val_ds,
    epochs=EPOCHS,
    callbacks=cbs,
    verbose=1
)

print("\nBest model saved to:", MODEL_PATH)
print("Logs saved to:", LOG_CSV)
print("Train/Val sizes:", n_train, n_val)
```

```
2025-09-07 15:30:34.604950: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
```

```
Found 5040 samples → train: 4032, val: 1008
Epoch 1/30
```

```
WARNING: All log messages before absl::InitializeLog() is called are
written to STDERR
I0000 00:00:1757251842.612781    6472 service.cc:146] XLA service
0x788924004030 initialized for platform CUDA (this does not guarantee
that XLA will be used). Devices:
I0000 00:00:1757251842.612831    6472 service.cc:154]   StreamExecutor
device (0): NVIDIA GeForce RTX 3070 Laptop GPU, Compute Capability 8.6
2025-09-07 15:30:42.918667: I
tensorflow/compiler/mlir/tensorflow/utils/dump_mlir_util.cc:268]
disabling MLIR crash reproducer, set env var
`MLIR_CRASH_REPRODUCER_DIRECTORY` to enable.
2025-09-07 15:30:44.427967: I
external/local_xla/xla/stream_executor/cuda/cuda_dnn.cc:531] Loaded
cuDNN version 8907
```

```
      4/Unknown 15s 49ms/step - categorical_accuracy: 0.2832 - loss:
1.6096
```

```
I0000 00:00:1757251851.297516    6472 device_compiler.h:188] Compiled
cluster using XLA!  This line is logged at most once for the lifetime
of the process.
```

```
    126/Unknown 21s 43ms/step - categorical_accuracy: 0.5181 - loss:
1.2841

2025-09-07 15:30:56.772246: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
	 [[{{node IteratorGetNext}}]]
/media/andi/ssd2/dev/code/RAILS/.venv/lib/python3.10/site-packages/
keras/src/trainers/epoch_iterator.py:164: UserWarning: Your input ran
out of data; interrupting training. Make sure that your dataset or
generator can generate at least `steps_per_epoch * epochs` batches.
You may need to use the `.repeat()` function when building your
dataset.
  self._interrupted_warning()
2025-09-07 15:31:00.735782: I
external/local_xla/xla/stream_executor/cuda/cuda_asm_compiler.cc:393]
ptxas warning : Registers are spilled to local memory in function
'gemm_fusion_dot_1535', 176 bytes spill stores, 468 bytes spill loads



Epoch 1: val_loss improved from None to 0.38664, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:09.077460: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
	 [[{{node IteratorGetNext}}]]
2025-09-07 15:31:09.077500: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:09.077509: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 34s 151ms/step - categorical_accuracy:
0.7237 - loss: 0.9723 - val_categorical_accuracy: 0.9673 - val_loss:
0.3866
Epoch 2/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 46ms/step - categorical_accuracy:
0.9526 - loss: 0.3280
Epoch 2: val_loss improved from 0.38664 to 0.12292, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:17.784047: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
	 [[{{node IteratorGetNext}}]]
2025-09-07 15:31:17.784081: I
```

```
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:17.784096: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 67ms/step - categorical_accuracy:
0.9616 - loss: 0.2575 - val_categorical_accuracy: 0.9812 - val_loss:
0.1229
Epoch 3/30
125/126 ━━━━━━━━━━━━━━━━━━━━ 0s 44ms/step - categorical_accuracy:
0.9733 - loss: 0.1358
Epoch 3: val_loss improved from 0.12292 to 0.07104, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:26.106470: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:26.106493: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 8s 64ms/step - categorical_accuracy:
0.9759 - loss: 0.1213 - val_categorical_accuracy: 0.9851 - val_loss:
0.0710
Epoch 4/30
125/126 ━━━━━━━━━━━━━━━━━━━━ 0s 45ms/step - categorical_accuracy:
0.9779 - loss: 0.0935

2025-09-07 15:31:32.739756: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 4: val_loss improved from 0.07104 to 0.05244, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:34.480270: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
	 [[{{node IteratorGetNext}}]]
2025-09-07 15:31:34.480297: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 8s 66ms/step - categorical_accuracy:
0.9812 - loss: 0.0800 - val_categorical_accuracy: 0.9871 - val_loss:
0.0524
Epoch 5/30
```

```
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 45ms/step - categorical_accuracy:
0.9813 - loss: 0.0682

2025-09-07 15:31:41.071207: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:41.071245: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 5: val_loss improved from 0.05244 to 0.04316, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:42.902424: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:42.902458: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 8s 65ms/step - categorical_accuracy:
0.9839 - loss: 0.0603 - val_categorical_accuracy: 0.9901 - val_loss:
0.0432
Epoch 6/30
125/126 ━━━━━━━━━━━━━━━━━━━━ 0s 45ms/step - categorical_accuracy:
0.9891 - loss: 0.0510
Epoch 6: val_loss improved from 0.04316 to 0.03794, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:51.105328: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:51.105388: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 8s 65ms/step - categorical_accuracy:
0.9888 - loss: 0.0476 - val_categorical_accuracy: 0.9901 - val_loss:
0.0379
Epoch 7/30
125/126 ━━━━━━━━━━━━━━━━━━━━ 0s 44ms/step - categorical_accuracy:
0.9897 - loss: 0.0430
Epoch 7: val_loss improved from 0.03794 to 0.03502, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:31:59.306340: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
```

```
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:31:59.306362: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 8s 65ms/step - categorical_accuracy:
0.9901 - loss: 0.0405 - val_categorical_accuracy: 0.9911 - val_loss:
0.0350
Epoch 8/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 46ms/step - categorical_accuracy:
0.9912 - loss: 0.0405
Epoch 8: val_loss improved from 0.03502 to 0.03319, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:32:07.823442: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
	 [[{{node IteratorGetNext}}]]
2025-09-07 15:32:07.823484: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:32:07.823497: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 67ms/step - categorical_accuracy:
0.9923 - loss: 0.0373 - val_categorical_accuracy: 0.9911 - val_loss:
0.0332
Epoch 9/30
125/126 ━━━━━━━━━━━━━━━━━━━━ 0s 48ms/step - categorical_accuracy:
0.9918 - loss: 0.0335
Epoch 9: val_loss improved from 0.03319 to 0.03083, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:32:16.750770: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:32:16.750792: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 71ms/step - categorical_accuracy:
0.9928 - loss: 0.0294 - val_categorical_accuracy: 0.9921 - val_loss:
0.0308
Epoch 10/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 50ms/step - categorical_accuracy:
0.9913 - loss: 0.0306
Epoch 10: val_loss improved from 0.03083 to 0.02899, saving model to
```

```
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:32:26.082946: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:32:26.082971: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 73ms/step - categorical_accuracy:
0.9936 - loss: 0.0248 - val_categorical_accuracy: 0.9921 - val_loss:
0.0290
Epoch 11/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 51ms/step - categorical_accuracy:
0.9919 - loss: 0.0299
Epoch 11: val_loss improved from 0.02899 to 0.02734, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:32:35.459842: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:32:35.459868: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 75ms/step - categorical_accuracy:
0.9933 - loss: 0.0263 - val_categorical_accuracy: 0.9931 - val_loss:
0.0273
Epoch 12/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 53ms/step - categorical_accuracy:
0.9960 - loss: 0.0220
Epoch 12: val_loss did not improve from 0.02734
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 69ms/step - categorical_accuracy:
0.9950 - loss: 0.0215 - val_categorical_accuracy: 0.9950 - val_loss:
0.0276
Epoch 13/30
  2/126 ━━━━━━━━━━━━━━━━━━━━ 6s 51ms/step - categorical_accuracy:
0.9766 - loss: 0.1291

2025-09-07 15:32:45.300681: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:32:45.300706: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 54ms/step - categorical_accuracy:
0.9934 - loss: 0.0264
Epoch 13: val_loss improved from 0.02734 to 0.02708, saving model to
```

```
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:32:54.275404: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:32:54.275427: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 78ms/step - categorical_accuracy:
0.9945 - loss: 0.0216 - val_categorical_accuracy: 0.9921 - val_loss:
0.0271
Epoch 14/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 54ms/step - categorical_accuracy:
0.9955 - loss: 0.0170

2025-09-07 15:33:02.062307: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:33:02.062354: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 14: val_loss improved from 0.02708 to 0.02589, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:33:04.164357: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:33:04.164383: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 77ms/step - categorical_accuracy:
0.9963 - loss: 0.0157 - val_categorical_accuracy: 0.9931 - val_loss:
0.0259
Epoch 15/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 53ms/step - categorical_accuracy:
0.9972 - loss: 0.0153
Epoch 15: val_loss improved from 0.02589 to 0.02499, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras
126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 77ms/step - categorical_accuracy:
0.9968 - loss: 0.0156 - val_categorical_accuracy: 0.9931 - val_loss:
0.0250
Epoch 16/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 55ms/step - categorical_accuracy:
0.9948 - loss: 0.0180
```

```
Epoch 16: val_loss did not improve from 0.02499
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 72ms/step - categorical_accuracy:
0.9963 - loss: 0.0152 - val_categorical_accuracy: 0.9931 - val_loss:
0.0254
Epoch 17/30
  1/126 ━━━━━━━━━━━━━━━━━━━━ 21s 170ms/step - categorical_accuracy:
1.0000 - loss: 0.0158

2025-09-07 15:33:23.895740: I
tensorflow/core/framework/local_rendezvous.cc:404] Local rendezvous is
aborting with status: OUT_OF_RANGE: End of sequence
	 [[{{node IteratorGetNext}}]]
2025-09-07 15:33:23.895781: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:33:23.895794: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 54ms/step - categorical_accuracy:
0.9974 - loss: 0.0129
Epoch 17: val_loss improved from 0.02499 to 0.02436, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:33:32.856651: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:33:32.856680: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 79ms/step - categorical_accuracy:
0.9968 - loss: 0.0128 - val_categorical_accuracy: 0.9940 - val_loss:
0.0244
Epoch 18/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 54ms/step - categorical_accuracy:
0.9975 - loss: 0.0141
Epoch 18: val_loss improved from 0.02436 to 0.02363, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:33:42.858270: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:33:42.858292: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 77ms/step - categorical_accuracy:
0.9973 - loss: 0.0132 - val_categorical_accuracy: 0.9931 - val_loss:
```

```
0.0236
Epoch 19/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 54ms/step - categorical_accuracy:
0.9950 - loss: 0.0153
Epoch 19: val_loss did not improve from 0.02363
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 70ms/step - categorical_accuracy:
0.9958 - loss: 0.0133 - val_categorical_accuracy: 0.9940 - val_loss:
0.0240
Epoch 20/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 56ms/step - categorical_accuracy:
0.9956 - loss: 0.0136

2025-09-07 15:33:59.752030: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:33:59.752054: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 20: val_loss did not improve from 0.02363
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 73ms/step - categorical_accuracy:
0.9960 - loss: 0.0129 - val_categorical_accuracy: 0.9921 - val_loss:
0.0236
Epoch 21/30
  1/126 ━━━━━━━━━━━━━━━━━━━━ 20s 166ms/step - categorical_accuracy:
1.0000 - loss: 0.0046

2025-09-07 15:34:01.793828: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:34:01.793868: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 55ms/step - categorical_accuracy:
0.9979 - loss: 0.0128
Epoch 21: val_loss improved from 0.02363 to 0.02347, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:34:11.109349: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:34:11.109376: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 82ms/step - categorical_accuracy:
0.9975 - loss: 0.0122 - val_categorical_accuracy: 0.9940 - val_loss:
0.0235
```

```
Epoch 22/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 57ms/step - categorical_accuracy:
0.9958 - loss: 0.0132
Epoch 22: val_loss did not improve from 0.02347
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 74ms/step - categorical_accuracy:
0.9955 - loss: 0.0120 - val_categorical_accuracy: 0.9911 - val_loss:
0.0236
Epoch 23/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 55ms/step - categorical_accuracy:
0.9992 - loss: 0.0077

2025-09-07 15:34:28.654364: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:34:28.654385: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 23: val_loss improved from 0.02347 to 0.02162, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras
126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 80ms/step - categorical_accuracy:
0.9985 - loss: 0.0086 - val_categorical_accuracy: 0.9921 - val_loss:
0.0216
Epoch 24/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 58ms/step - categorical_accuracy:
0.9981 - loss: 0.0091
Epoch 24: val_loss did not improve from 0.02162
126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 75ms/step - categorical_accuracy:
0.9978 - loss: 0.0093 - val_categorical_accuracy: 0.9931 - val_loss:
0.0229
Epoch 25/30

2025-09-07 15:34:41.315128: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:34:41.315176: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 57ms/step - categorical_accuracy:
0.9979 - loss: 0.0081

2025-09-07 15:34:49.269186: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 25: val_loss improved from 0.02162 to 0.02113, saving model to
```

```
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:34:51.450710: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:34:51.450733: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 11s 82ms/step - categorical_accuracy:
0.9968 - loss: 0.0101 - val_categorical_accuracy: 0.9931 - val_loss:
0.0211
Epoch 26/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 56ms/step - categorical_accuracy:
0.9978 - loss: 0.0073

2025-09-07 15:34:59.580071: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:34:59.580128: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562


Epoch 26: val_loss did not improve from 0.02113
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 73ms/step - categorical_accuracy:
0.9973 - loss: 0.0078 - val_categorical_accuracy: 0.9931 - val_loss:
0.0213
Epoch 27/30
  1/126 ━━━━━━━━━━━━━━━━━━━━ 20s 164ms/step - categorical_accuracy:
1.0000 - loss: 0.0035

2025-09-07 15:35:01.678801: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:35:01.678825: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 58ms/step - categorical_accuracy:
0.9995 - loss: 0.0058
Epoch 27: val_loss did not improve from 0.02113
126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 76ms/step - categorical_accuracy:
0.9990 - loss: 0.0063 - val_categorical_accuracy: 0.9931 - val_loss:
0.0220
Epoch 28/30
  1/126 ━━━━━━━━━━━━━━━━━━━━ 17s 140ms/step - categorical_accuracy:
1.0000 - loss: 0.0019
```

```
2025-09-07 15:35:11.356563: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:35:11.356595: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 56ms/step - categorical_accuracy:
0.9957 - loss: 0.0100
Epoch 28: val_loss improved from 0.02113 to 0.02102, saving model to
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras

2025-09-07 15:35:20.582261: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:35:20.582285: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 79ms/step - categorical_accuracy:
0.9978 - loss: 0.0072 - val_categorical_accuracy: 0.9940 - val_loss:
0.0210
Epoch 29/30
126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 58ms/step - categorical_accuracy:
0.9986 - loss: 0.0071
Epoch 29: val_loss did not improve from 0.02102
126/126 ━━━━━━━━━━━━━━━━━━━━ 9s 74ms/step - categorical_accuracy:
0.9990 - loss: 0.0063 - val_categorical_accuracy: 0.9931 - val_loss:
0.0223
Epoch 30/30
  1/126 ━━━━━━━━━━━━━━━━━━━━ 19s 158ms/step - categorical_accuracy:
1.0000 - loss: 0.0067

2025-09-07 15:35:30.739683: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:35:30.739707: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562

126/126 ━━━━━━━━━━━━━━━━━━━━ 0s 60ms/step - categorical_accuracy:
0.9970 - loss: 0.0084
Epoch 30: val_loss did not improve from 0.02102
126/126 ━━━━━━━━━━━━━━━━━━━━ 10s 77ms/step - categorical_accuracy:
0.9975 - loss: 0.0075 - val_categorical_accuracy: 0.9940 - val_loss:
0.0212
Restoring model weights from the end of the best epoch: 28.

Best model saved to:
```

```
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/PT_Mu
ltiClassResNet50_Trackbed.keras
Logs saved to:
outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-153036/train
ing_log.csv
Train/Val sizes: 4032 1008

2025-09-07 15:35:40.465159: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 3354959430978063621
2025-09-07 15:35:40.465230: I
tensorflow/core/framework/local_rendezvous.cc:423] Local rendezvous
recv item cancelled. Key hash: 4399490566733988562
```

5. Trainingskurven: Verlaufsanalyse

Was:

- Visualisierung von Loss und Categorical Accuracy über alle Epochen
- Separate Kurven für Training und Validation zur Overfitting-Erkennung

Warum:

- **Konvergenz-Analyse:** Überprüfung ob das Training erfolgreich konvergiert ist
- **Overfitting-Detektion:** Auseinanderlaufende Train/Val-Kurven zeigen Überanpassung
- **Model-Validierung:** Visueller Nachweis einer stabilen und erfolgreichen Optimierung

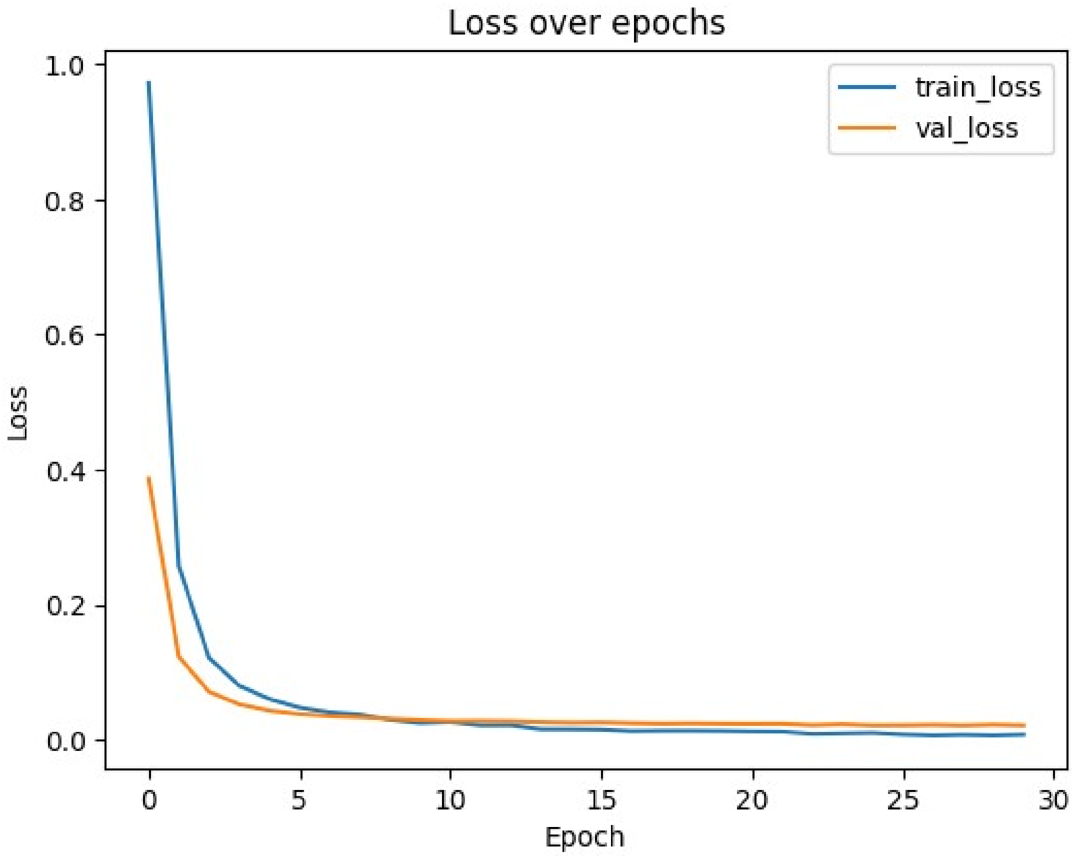
Interpretation:

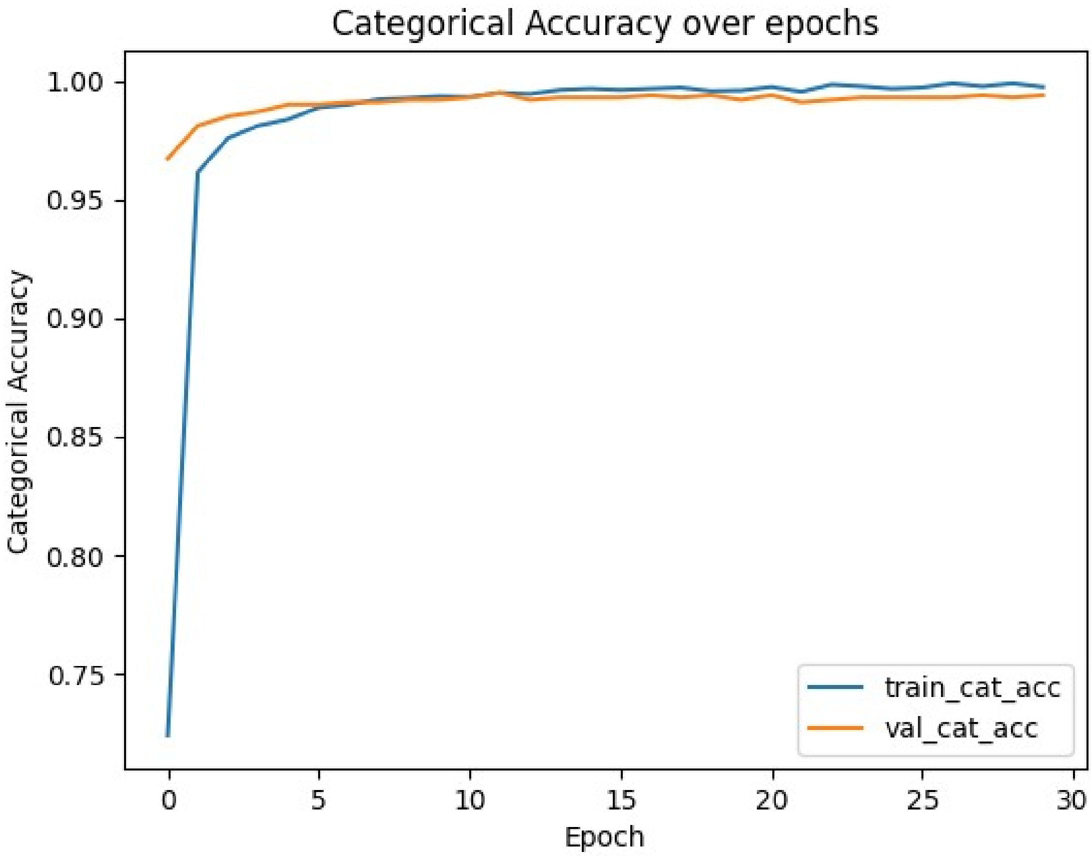
- **Idealer Verlauf:** Beide Kurven sinken (Loss) bzw. steigen (Accuracy) und konvergieren
- **Overfitting:** Training-Metrik verbessert sich weiter, während Validation stagniert oder schlechter wird
- **Underfitting:** Beide Kurven haben noch nicht konvergiert und zeigen weiteres Verbesserungspotential

Outputs:

- Zwei Matplotlib-Plots: Loss-Verlauf und Accuracy-Verlauf
- Visuelle Dokumentation der Trainingsqualität

```python
import matplotlib.pyplot as plt

# Plot: Loss
plt.figure()
plt.plot(history.history.get('loss', []), label='train_loss')
plt.plot(history.history.get('val_loss', []), label='val_loss')
plt.title('Loss over epochs')
plt.xlabel('Epoch')
plt.ylabel('Loss')
plt.legend()
plt.show()

# Plot: Categorical Accuracy
plt.figure()
plt.plot(history.history.get('categorical_accuracy', []),
label='train_cat_acc')
plt.plot(history.history.get('val_categorical_accuracy', []),
label='val_cat_acc')
plt.title('Categorical Accuracy over epochs')
plt.xlabel('Epoch')
plt.ylabel('Categorical Accuracy')
plt.legend()
plt.show()
```





6. Evaluation: Detaillierte Leistungsanalyse auf Hold-out-Datensatz

Was:

- Umfassende Evaluation des besten Modells auf dem separaten EVAL-Datensatz
- Berechnung aller relevanten Klassifikationsmetriken und detaillierte Fehleranalyse

Berechnete Metriken:

- **Confusion Matrix** (Gesamt-Übersicht der Klassifikationsergebnisse)
- **Pro Klasse:** Precision, Recall (Sensitivity), Specificity, F1-Score, Accuracy
- **Fehlerraten:** Type I/II Error Rates
- **Aggregate Metriken:** Macro (ungewichtet) und Weighted (gewichtet) Averages

Gespeicherte Artefakte:

- `evaluation_summary_*.csv` — Vollständige Metrik-Tabelle
- `confusion_matrix_*.csv` — Raw Counts der Confusion Matrix
- `false_inferences_*.json` — Dateinamen aller FP/FN + Fehlklassifikationen (mit Vorhersage vs. wahre Klasse)

Warum:

- **Objektive Bewertung:** Hold-out-Set war nie in Training/Validation involviert
- **Detaillierte Analyse:** Pro-Klassen-Metriken decken klassenspezifische Schwächen auf
- **Fehleranalyse:** Identifikation problematischer Bilder für weitere Untersuchungen
- **Reproduzierbarkeit:** Alle Metriken und Fehler werden persistent gespeichert

Visualisierungen:

- **Confusion Matrix Heatmap** mit Zahlenwerten
- **F1-Score Balkendiagramm** pro Klasse
- **Klassenverteilung** des Evaluationsdatensatzes
- **False Positives vs. False Negatives** Vergleich pro Klasse

Outputs:

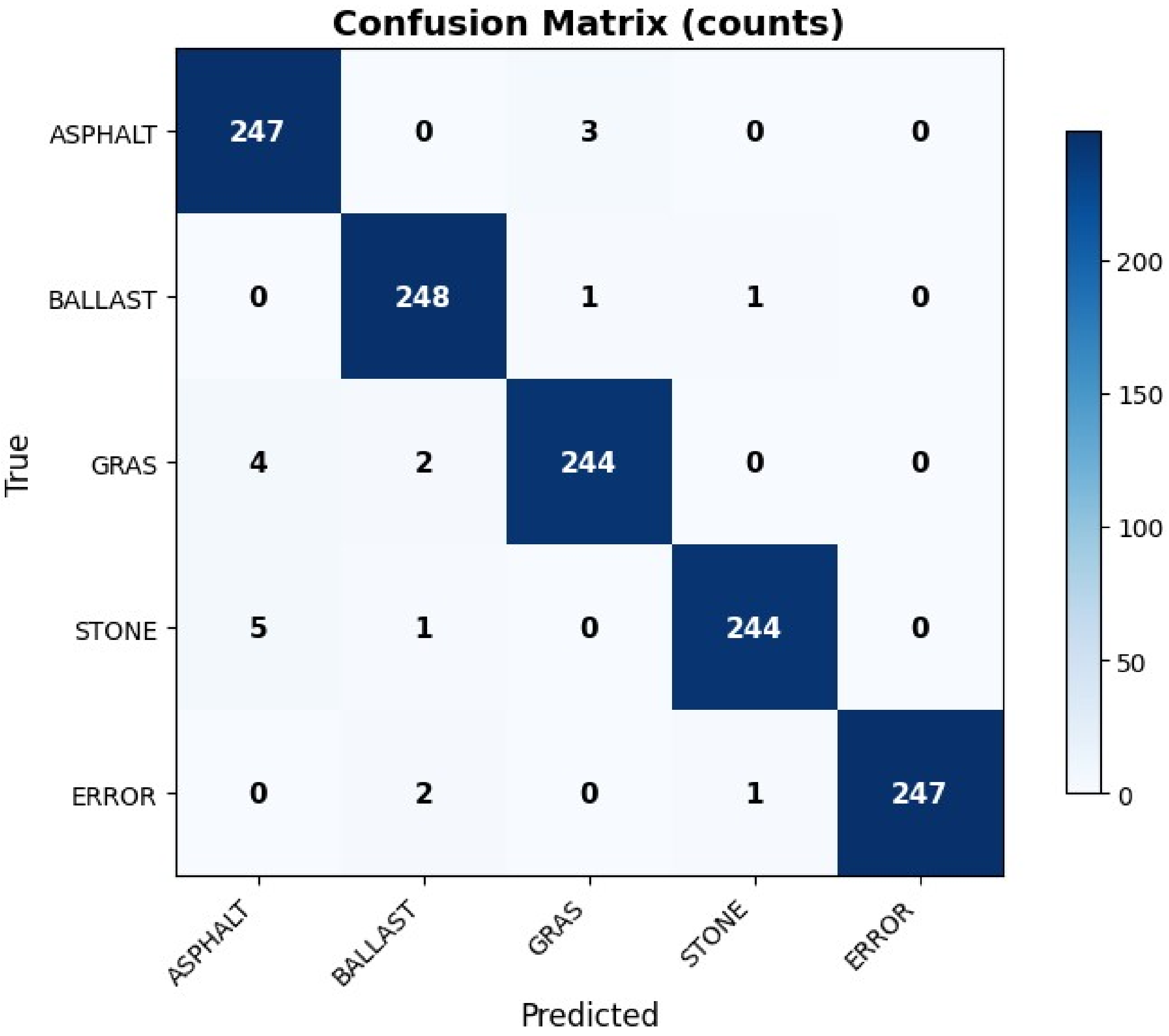
- CSV/JSON-Dateien mit allen Metriken und Fehlern
- Vier Visualisierungen zur Ergebnisinterpretation
- Konsolen-Summary mit Kernmetriken (Overall Accuracy, Macro F1, etc.)

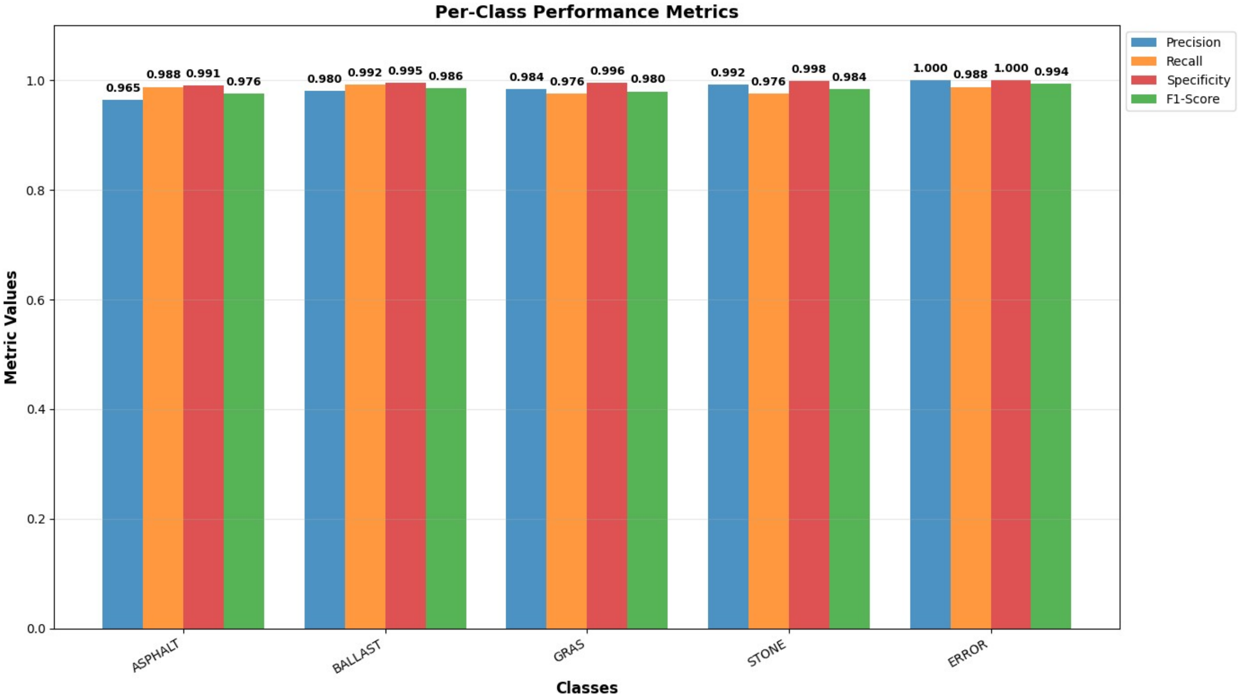
```
from sklearn.metrics import confusion_matrix
import csv
import math
import numpy as np
import matplotlib.pyplot as plt

# Ensure we load the best-saved model from disk (even if EarlyStopping
restored in-memory weights)
best_model = tf.keras.models.load_model(MODEL_PATH, compile=False)

# Predict across the eval set
all_true_idx = []
all_pred_idx = []
false_dict = {
    'false_positive': {c: [] for c in CLASSES},
    'false_negative': {c: [] for c in CLASSES},
    'misclassified': []
}

for batch_imgs, batch_trues, batch_fns in eval_ds:
    probs = best_model.predict(batch_imgs, verbose=0)
    pred_idx = np.argmax(probs, axis=1)
    true_idx = np.argmax(batch_trues.numpy(), axis=1)

    all_pred_idx.extend(list(pred_idx))
    all_true_idx.extend(list(true_idx))

    # Track errors with filenames + confidence
    for ti, pi, fn, p in zip(true_idx, pred_idx, batch_fns.numpy(),
probs):
        filename = fn.decode('utf-8') if isinstance(fn, (bytes,
bytearray)) else str(fn)
        conf = float(np.max(p))
        if ti != pi:
            false_dict['misclassified'].append({
                'filename': filename,
                'true_class': CLASSES[int(ti)],
                'predicted_class': CLASSES[int(pi)],
                'confidence': conf
            })
        # Per-class FP/FN views
        for ci in range(NUM_CLASSES):
            # Binary view for class ci
            true_bin = (ti == ci)
            pred_bin = (pi == ci)
            if (not true_bin) and pred_bin:
                false_dict['false_positive']
[CLASSES[ci]].append(f"{filename}_{conf:.3f}")
            if true_bin and (not pred_bin):
                false_dict['false_negative']
[CLASSES[ci]].append(f"{filename}_{conf:.3f}")

all_true_idx = np.array(all_true_idx, dtype=int)
all_pred_idx = np.array(all_pred_idx, dtype=int)

# Overall confusion matrix (NUM_CLASSES x NUM_CLASSES)
overall_conf = confusion_matrix(all_true_idx, all_pred_idx,
labels=list(range(NUM_CLASSES)))

# Build per-class binary TP/FP/FN/TN
binary_conf = np.zeros((NUM_CLASSES, 4), dtype=float)  # TP, FP, FN,
TN
for ci in range(NUM_CLASSES):
    # For class ci: positive if true==ci / predicted==ci
    tp = np.sum((all_true_idx == ci) & (all_pred_idx == ci))
    fp = np.sum((all_true_idx != ci) & (all_pred_idx == ci))
    fn = np.sum((all_true_idx == ci) & (all_pred_idx != ci))
    tn = np.sum((all_true_idx != ci) & (all_pred_idx != ci))
    binary_conf[ci] = [tp, fp, fn, tn]

def _safe_div(a, b):
    return (a / b) if b != 0 else 0.0

# Compute metrics
tps, fps, fns, tns = binary_conf[:,0], binary_conf[:,1],
binary_conf[:,2], binary_conf[:,3]
accuracies   = np.array([_safe_div(tp+tn, tp+fp+fn+tn) for tp,fp,fn,tn
in binary_conf])
recalls      = np.array([_safe_div(tp, tp+fn) for tp,fn in
zip(tps,fns)])              # aka sensitivity
specificity  = np.array([_safe_div(tn, tn+fp) for tn,fp in
zip(tns,fps)])
typeI_err    = np.array([_safe_div(fp, fp+tn) for fp,tn in
zip(fps,tns)])
typeII_err   = np.array([_safe_div(fn, tp+fn) for tp,fn in
zip(tps,fns)])
precisions   = np.array([_safe_div(tp, tp+fp) for tp,fp in
zip(tps,fps)])
f1_scores    = np.array([_safe_div(2*p*r, p+r) for p,r in
zip(precisions,recalls)])

overall_acc  = _safe_div(np.trace(overall_conf), np.sum(overall_conf))

macro_precision = float(np.mean(precisions)) if len(precisions) else
0.0
macro_recall    = float(np.mean(recalls))    if len(recalls)    else
0.0
macro_f1        = float(np.mean(f1_scores))  if len(f1_scores)  else
0.0

supports = tps + fns
total    = np.sum(supports) if np.sum(supports) > 0 else 1.0

metrics = {
    "Accuracy": list(map(float, accuracies)) + [float(overall_acc)],
    "Precision": list(map(float, precisions)) +
[float(macro_precision)],
    "Recall": list(map(float, recalls)) + [float(macro_recall)],
    "Specificity": list(map(float, specificity)) +
[float(np.mean(specificity) if len(specificity) else 0.0)],
    "F1-Score": list(map(float, f1_scores)) + [float(macro_f1)],
    "Type I Error": list(map(float, typeI_err)) +
[float(np.mean(typeI_err) if len(typeI_err) else 0.0)],
    "Type II Error": list(map(float, typeII_err)) +
[float(np.mean(typeII_err) if len(typeII_err) else 0.0)]
}

# Save CSV metrics and confusion matrix + false inferences JSON
eval_csv = str(Path(run_dir) / f"evaluation_summary_{MODEL_NAME}.csv")
conf_csv = str(Path(run_dir) / f"confusion_matrix_{MODEL_NAME}.csv")
false_json = str(Path(run_dir) /
f"false_inferences_{MODEL_NAME}.json")

with open(eval_csv, 'w', newline='') as f:
    writer = csv.writer(f)
    writer.writerow(["Metric", "Class", "Value"])
    # per-class
    for name, vals in metrics.items():
        if name.startswith("Weighted"):
            continue
        for idx, v in enumerate(vals[:-1]):
            writer.writerow([name, CLASSES[idx], v])
    # macro/overall
    writer.writerow([])
    writer.writerow(["Metric", "Overall/Average", "Value"])
    for name, vals in metrics.items():
        if name.startswith("Weighted"):
            writer.writerow([name, "Weighted", vals[0]])
        else:
            writer.writerow([name, "Macro Average", vals[-1]])

np.savetxt(conf_csv, overall_conf, delimiter=',', fmt='%d',
header=','.join(CLASSES), comments='')

with open(false_json, 'w') as jf:
    json.dump(false_dict, jf, indent=2)

print("Saved:", eval_csv)
print("Saved:", conf_csv)
print("Saved:", false_json)

# --- Visualizations
-----------------------------------------------------------

# (1) Confusion matrix heatmap with better color scheme
plt.figure(figsize=(8, 6))
im = plt.imshow(overall_conf, cmap='Blues', interpolation='nearest')
plt.title('Confusion Matrix (counts)', fontsize=14, fontweight='bold')
plt.xticks(ticks=range(NUM_CLASSES), labels=CLASSES, rotation=45,
ha='right')
plt.yticks(ticks=range(NUM_CLASSES), labels=CLASSES)
plt.xlabel('Predicted', fontsize=12)
plt.ylabel('True', fontsize=12)

# Add text annotations with good contrast
for i in range(NUM_CLASSES):
    for j in range(NUM_CLASSES):
        text_color = 'white' if overall_conf[i, j] >
overall_conf.max() / 2 else 'black'
        plt.text(j, i, str(overall_conf[i, j]), ha='center',
va='center',
                color=text_color, fontsize=11, fontweight='bold')

plt.colorbar(im, shrink=0.8)
plt.tight_layout()
plt.show()

# (2) Comprehensive Metrics Bar Chart
fig, ax = plt.subplots(figsize=(14, 8))

# Prepare data for visualization
```

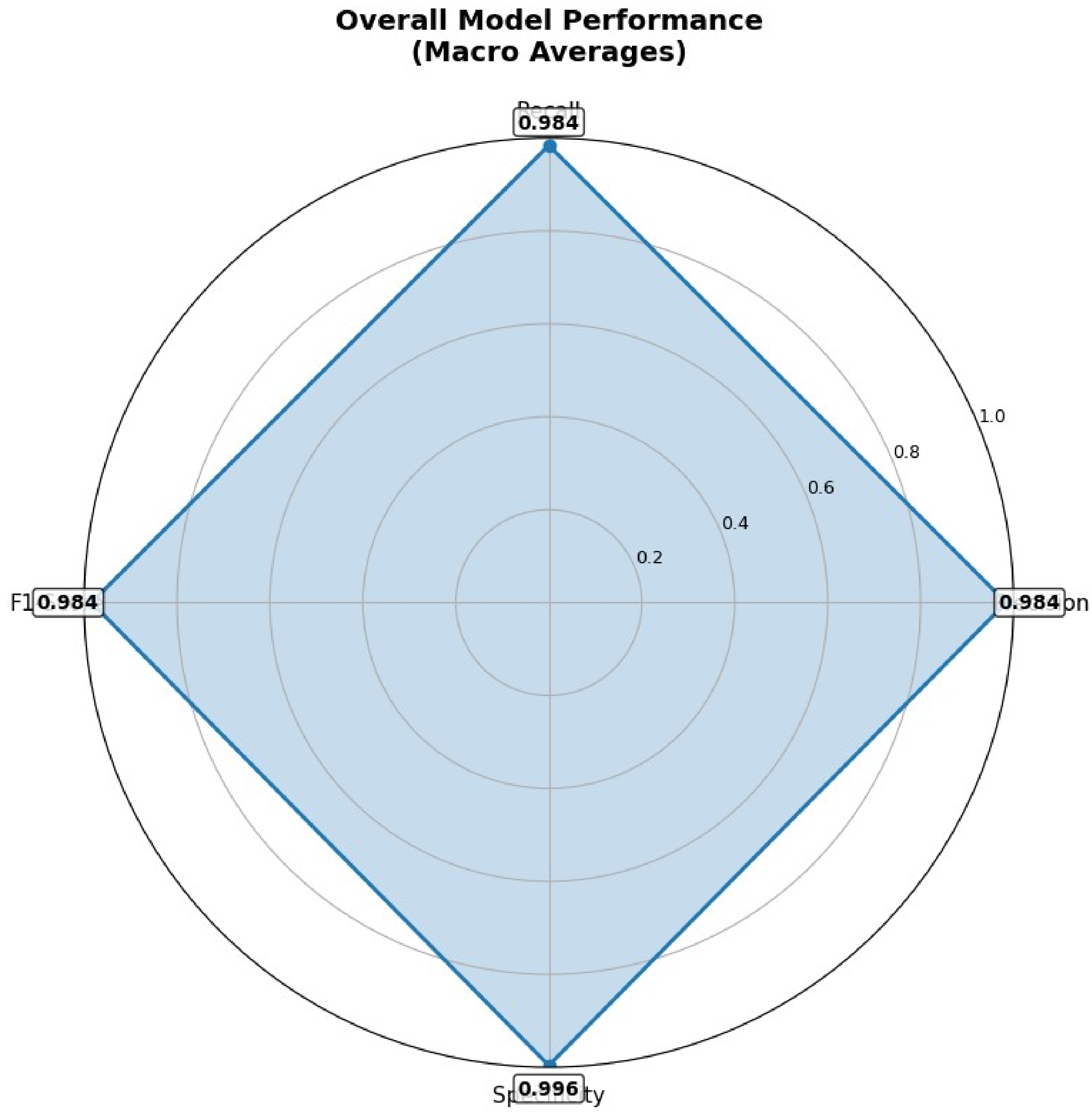
```
metric_names = ['Precision', 'Recall', 'Specificity', 'F1-Score']
x = np.arange(len(CLASSES))
width = 0.2

colors = ['#1f77b4', '#ff7f0e', '#d62728', '#2ca02c']

for i, metric in enumerate(metric_names):
    values = metrics[metric][:-1]  # Exclude macro average
    bars = ax.bar(x + i*width, values, width, label=metric,
color=colors[i], alpha=0.8)

    # Add value labels on top of bars
    for j, (bar, val) in enumerate(zip(bars, values)):
        height = bar.get_height()
        ax.text(bar.get_x() + bar.get_width()/2., height + 0.01,
                f'{val:.3f}', ha='center', va='bottom', fontsize=9,
fontweight='bold')

ax.set_xlabel('Classes', fontsize=12, fontweight='bold')
ax.set_ylabel('Metric Values', fontsize=12, fontweight='bold')
ax.set_title('Per-Class Performance Metrics', fontsize=14,
fontweight='bold')
ax.set_xticks(x + width * 1.5)
ax.set_xticklabels(CLASSES, rotation=30, ha='right')
ax.legend(loc='upper left', bbox_to_anchor=(1, 1))
ax.set_ylim(0, 1.1)
ax.grid(True, alpha=0.3, axis='y')

plt.tight_layout()
plt.show()

# (3) Alternative Suggestion: Radar Chart for Macro Metrics
fig, ax = plt.subplots(figsize=(8, 8),
subplot_kw=dict(projection='polar'))

# Macro metrics for radar chart
radar_metrics = ['Precision', 'Recall', 'F1-Score', 'Specificity']
radar_values = [metrics[m][-1] for m in radar_metrics]  # Get macro
averages

# Number of variables
N = len(radar_metrics)

# Compute angle for each axis
angles = [n / float(N) * 2 * np.pi for n in range(N)]
angles += angles[:1]  # Complete the circle

# Add values
radar_values += radar_values[:1]  # Complete the circle
```

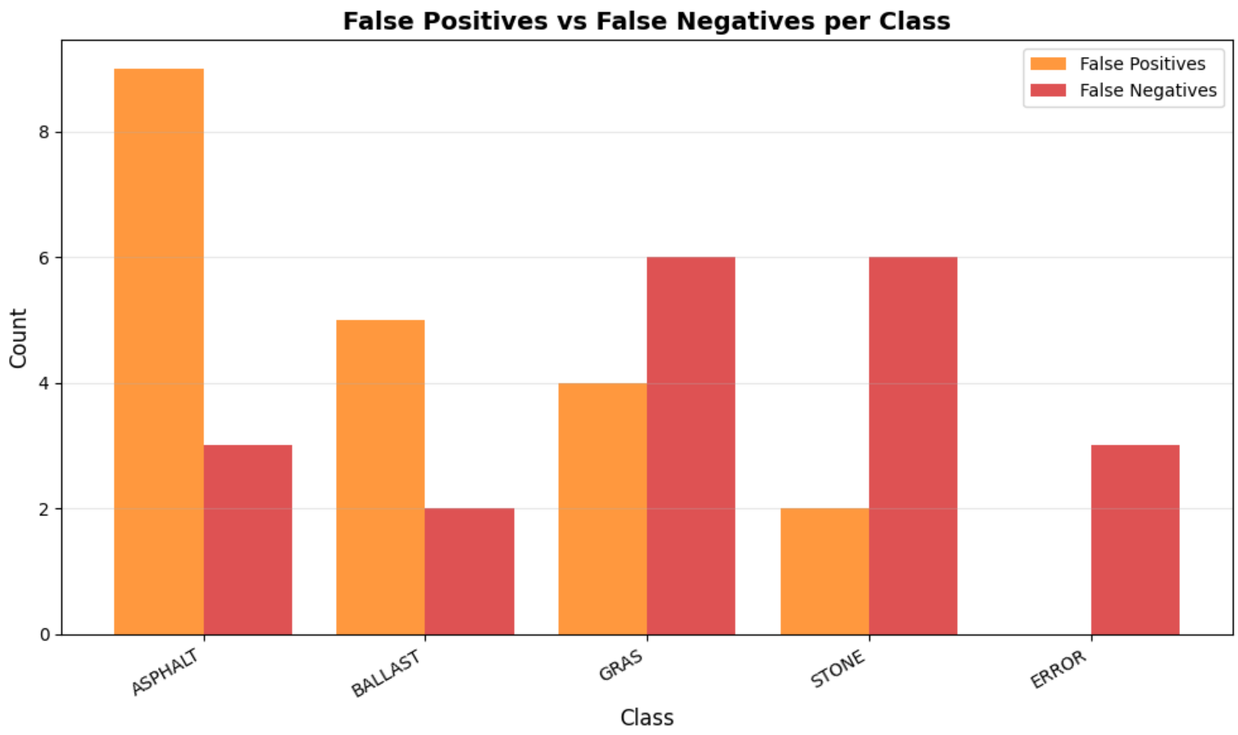
```
# Plot
ax.plot(angles, radar_values, 'o-', linewidth=2, label='Macro
Average', color='#1f77b4')
ax.fill(angles, radar_values, alpha=0.25, color='#1f77b4')

# Add labels
ax.set_xticks(angles[:-1])
ax.set_xticklabels(radar_metrics, fontsize=11)
ax.set_ylim(0, 1)
ax.set_yticks([0.2, 0.4, 0.6, 0.8, 1.0])
ax.set_yticklabels(['0.2', '0.4', '0.6', '0.8', '1.0'], fontsize=9)
ax.grid(True)

# Add value labels
for angle, value, metric in zip(angles[:-1], radar_values[:-1],
radar_metrics):
    ax.text(angle, value + 0.05, f'{value:.3f}', ha='center',
va='center',
            fontsize=10, fontweight='bold',
            bbox=dict(boxstyle='round,pad=0.2', facecolor='white',
alpha=0.8))

ax.set_title('Overall Model Performance\n(Macro Averages)',
fontsize=14, fontweight='bold', pad=20)
plt.tight_layout()
plt.show()

# (4) False Positives vs False Negatives per class
fp_counts = [len(false_dict['false_positive'][c]) for c in CLASSES]
fn_counts = [len(false_dict['false_negative'][c]) for c in CLASSES]

plt.figure(figsize=(10, 6))
x = np.arange(NUM_CLASSES)
plt.bar(x - 0.2, fp_counts, width=0.4, label='False Positives',
color='#ff7f0e', alpha=0.8)
plt.bar(x + 0.2, fn_counts, width=0.4, label='False Negatives',
color='#d62728', alpha=0.8)
plt.xticks(x, CLASSES, rotation=30, ha='right')
plt.title('False Positives vs False Negatives per Class', fontsize=14,
fontweight='bold')
plt.xlabel('Class', fontsize=12)
plt.ylabel('Count', fontsize=12)
plt.legend()
plt.grid(True, alpha=0.3, axis='y')
plt.tight_layout()
plt.show()

print("\n=== EVAL SUMMARY ===")
print(f"Overall accuracy: {overall_acc:.4f}")
print(f"Macro F1-Score:  {macro_f1:.4f}")
print(f"Total samples:    {int(np.sum(overall_conf))}")
print(f"Total misclass.:  {len(false_dict['misclassified'])}")
```

```
Saved: outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-
153036/evaluation_summary_PT_MultiClassResNet50_Trackbed.csv
Saved: outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-
153036/confusion_matrix_PT_MultiClassResNet50_Trackbed.csv
Saved: outputs_trackbed/PT_MultiClassResNet50_Trackbed__20250907-
153036/false_inferences_PT_MultiClassResNet50_Trackbed.json
```




Per-Class Performance Metrics
Metric Values
0.0
0.2
0.4
0.6
0.8
1.0
Classes
ASPHALT
BALLAST
GRAS
STONE
ERROR
0.965
0.988
0.991
0.976
0.980
0.992
0.995
0.986
0.984
0.976
0.996
0.980
0.992
0.976
0.998
0.984
1.000
0.988
1.000
0.994
Precision
Recall
Specificity
F1-Score


Overall Model Performance
(Macro Averages)
Recall
0.984
Precision
0.984
Specificity
0.996
F1
0.984
0.2
0.4
0.6
0.8
1.0



```
=== EVAL SUMMARY ===
Overall accuracy: 0.9840
Macro F1-Score:  0.9840
Total samples:    1250
Total misclass.:  20
```

7. Qualitative Stichprobe: Vorhersage-Visualisierung

Was:

- Visualisierung einiger Vorhersagen mit wahren Labels und Konfidenzwerten
- Direkte Anzeige aus `eval_ds` Tensoren (nicht von Festplatte)

Warum:

- **Qualitative Kontrolle:** Visueller Eindruck der Modell-Performance auf echten Bildern
- **Fehlerverständnis:** Erkennung von Mustern bei Fehlklassifikationen
- **Konfidenz-Analyse:** Bewertung der Modell-Sicherheit bei verschiedenen Vorhersagen

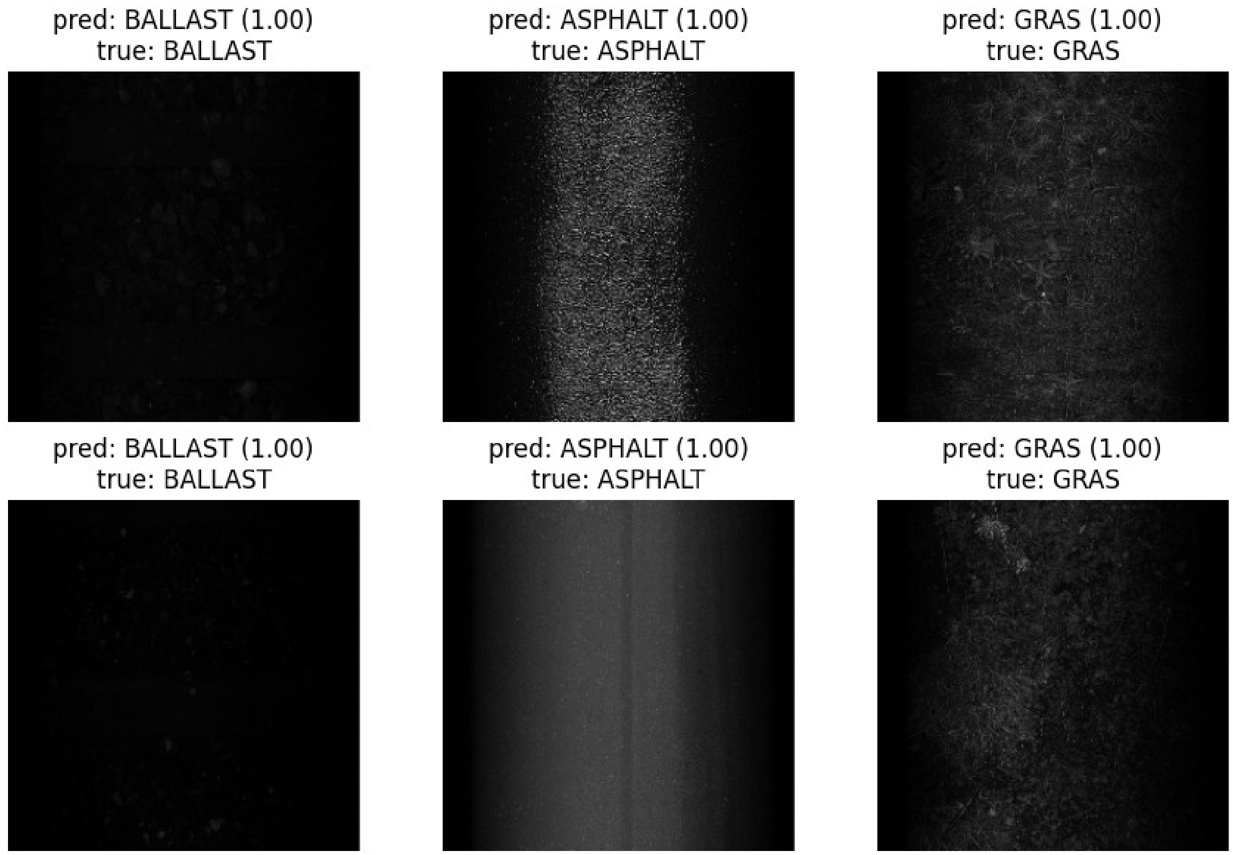
Interpretation:

- **Korrekte Vorhersagen:** Hohe Konfidenz bei richtigen Klassifikationen ist wünschenswert
- **Fehlklassifikationen:** Niedrige Konfidenz kann auf schwierige/mehrdeutige Bilder hinweisen
- **Systematische Fehler:** Wiederholte Verwechslungen zwischen bestimmten Klassen

Outputs:

- Grid-Anzeige mit 6 Beispielbildern
- Je Bild: Vorhersage, Konfidenz, wahre Klasse

```
import matplotlib.pyplot as plt

def show_eval_samples(ds, model, k=6):
    imgs_shown = 0
    for imgs, labels, fns in ds:
        probs = model.predict(imgs, verbose=0)
        pred_idx = np.argmax(probs, axis=1)
        true_idx = np.argmax(labels.numpy(), axis=1)

        b = imgs.shape[0]
        rows = int(math.ceil(min(k, b) / 3))
        cols = 3 if k >= 3 else min(k, b)

        plt.figure(figsize=(cols*3, rows*3))
        for i in range(min(k, b)):
            ax = plt.subplot(rows, cols, i+1)
            ax.imshow(imgs[i].numpy())
            pidx = int(pred_idx[i])
            tidx = int(true_idx[i])
            conf = float(np.max(probs[i]))
            ax.set_title(f"pred: {CLASSES[pidx]} ({conf:.2f})\ntrue: {CLASSES[tidx]}")
            ax.axis('off')
        plt.tight_layout()
        plt.show()

        imgs_shown += min(k, b)
        if imgs_shown >= k:
            break

# Uncomment to preview a few eval samples (set k as needed)
show_eval_samples(eval_ds, best_model, k=6)
```



8. Dokumentation & Reproduzierbarkeit

Ergebnis: Dieses Notebook liefert ein vollständig trainiertes und evaluiertes CNN-Modell für die Schienenuntergrund-Klassifikation mit umfassender Dokumentation aller Parameter, Metriken und Ergebnisse. Die systematische Herangehensweise und detaillierte Evaluation bilden eine solide Grundlage für den praktischen Einsatz in der Gleisbett-Analyse.

Gespeicherte Artefakte:

- **Hyperparameter** und **Klassennamen** werden neben dem trainierten Modell im Run-Ordner gespeichert
- **Bestes Modell** (nach `val_loss`) wird im Keras-Format gespeichert: `<OUTPUT_DIR>/<MODEL_NAME>__<timestamp>/<MODEL_NAME>.keras`
- **Metriken und Confusion Matrix** sind als CSV-Dateien verfügbar
- **Fehlklassifikationen** werden als JSON gespeichert (mit Dateinamen und Konfidenzwerten)

Nächste Schritte (optional):

- **Fine-Tuning:** Einfrieren der oberen ResNet-Schichten aufheben (mit kleiner Learning Rate)
- **Klassenbalancierung:** Class-balanced Sampling / Focal Loss bei unbalancierten Datensätzen

- **Cross-Validation:** Integration verschiedener TFRecord-Shards (falls verfügbar)