## TVCalib: Camera Calibration for Sports Field Registration in Soccer

[https://mm4spa.github.io/tvcalib](https://mm4spa.github.io/tvcalib)

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Figure 1: Our proposed framework for 3D sports field registration: (1) *segment localization* performs instance segmentation and selects appropriate points with respective label from a known calibration object (3D model), and (2) our main contribution, the calibration module, which predicts camera parameters $\phi$ by iteratively minimizing the *segment reprojection loss*.

### Abstract

Sports field registration in broadcast videos is typically interpreted as the task of homography estimation, which provides a mapping between a planar field and the corresponding visible area of the image. In contrast to previous approaches, we consider the task as a camera calibration problem. First, we introduce a differentiable objective function that is able to learn the camera pose and focal length from segment correspondences (e.g., lines, point clouds), based on pixel-level annotations for segments of a known calibration object. The calibration module iteratively minimizes the segment reprojection error induced by the estimated camera parameters. Second, we propose a novel approach for 3D sports field registration from broadcast soccer images. Compared to the typical solution, which subsequently refines an initial estimation, our solution does it in one step. The proposed method is evaluated for sports field registration on two datasets and achieves superior results compared to two state-of-the-art approaches.

### 1. Introduction

Camera calibration is fundamental for numerous computer vision applications such as tracking, autonomous driving, robotics, augmented reality, etc. Existing literature has extensively studied this problem for fully calibrated, partially calibrated, and uncalibrated cameras in various settings [22], for different types of data (e.g., monocular images, image sequences, RGB-D images, etc.), and related tasks like 3D reconstruction. Broadcast videos of sports events are a widely available data source. The ability to calibrate from a single, moving camera with unknown and changing camera parameters enables various augmented reality [15] and sports analytics applications [13, 29].

The sports field serves as a calibration object (known dimensions according to the game rules). However, the non-visibility of appropriate keypoints in broadcast soccer videos [11] and the unknown focal length prevent a sufficiently accurate direct computation of a homography or intrinsics and extrinsics from 2D-3D (keypoint) correspondences [2, 18, 37, 38]. It has been shown that line [20, 27], area [6, 27, 30], point features with additional information [8, 11, 27] are more suitable for accurate sports field registration. Previous approaches [6, 8, 23, 27, 30, 32] treat the task as homography estimation instead of calibration despite the estimation of camera parameters enables further applications (e.g., virtual stadiums, automatic camera control, or offside detection). To date, homography-based approaches may provide camera parameters for a first coarse initial estimation, but the more accurate results are usually based on homography refinements.

In this paper, we suggest to consider sports field registration as a calibration task and estimate individual camera parameters (position, rotation, and focal length) of the stan-
dard pinhole camera model (and potential radial lens distortion coefficients) from an image without relying on keypoint correspondences between the image and 3D scene. Contrary to the dominant direction of first estimating an initial result and then refining it, our method does both in one step without relying on training data for the calibration part. Further, we use a dense representation of the visible field, i.e., directly leverage a small fraction of labeled pixel representing field segments instead of a (deep) image representation for both initial estimation [6, 30] or refinement [6, 8, 11, 23, 27, 30, 32].

We propose (1) a generic differentiable objective function that exploits the underlying primitives of a 3D object and measures its reprojection error. We additionally suggest (2) a novel framework for 3D sports field registration (TVCalib) from TV broadcast frames (Fig. 1), including semantic segmentation, point selection, the calibration module, and result verification, where the calibration module iteratively minimizes the segment reprojection loss. The effectiveness of our method is evaluated on two real-world soccer broadcast datasets (SoccerNet-Calibration [10] and World Cup 2014 (WC14) [20]), and we compare to state of the art in 2D sports field registration.

The rest of the paper is organized as follows. Sec. 2 provides an overview on 2D sports field registration and the related calibration task. In Sec. 3, we describe the proposed TVCalib in detail. Experimental results and a comparison with the state of the art are reported in Sec. 4, while Sec. 5 concludes the paper and outlines areas of future work.

2. Related Work on Sports Field Registration

Common to most approaches for sports field registration is that they predict homography matrices from main broadcast videos in team sports while the focus is on soccer. Early approaches rely on local feature matching in combination with Direct Linear Transform (DLT) for homography estimation [5, 16, 17, 28], and both line and ellipse features are already used (e.g., [17, 20, 27, 30]). More recent approaches rely on learning a representation of the visible sports field by performing different variants of semantic segmentation. Approaches directly predict or regress an initial homography matrix [8, 23, 27, 32] or search for the best matching homography in a reference database [6, 30, 31, 36] containing synthetic images with known homography matrices or camera parameters. This estimation is called initial estimation $H_{\text{init}}$ which is subsequently refined by the majority of approaches and considered as the relative (non-)affine image transformation $H_{\text{rel}}$ between the segmented input image and the predicted or retrieved image, finally resulting in $H = H_{\text{init}} H_{\text{rel}} \in \mathbb{R}^{3 \times 3}$.

Next, we review existing approaches regarding segmentation, initial estimation, refinement, and finally discuss how to access camera parameters.

Semantic Segmentation: Some approaches use handcrafted methods to detect lines, edges, ellipses, vanishing points (lines) or to perform area segmentation (see [12, 19] for an overview). Convolutional Neural Networks with increased receptive field (e.g., via dilated convolutions [7] or non-local blocks [35]) are used perform various types of image segmentation tasks, e.g., keypoint prediction, line segmentation, or area masking. Chen and Little [6] first remove the background and then predict a binary mask representing all field markings. Homayounfar et al. [20] predict points from specific line and circle segments. Other approaches segment the sports field into four different areas [30], or detect appropriate field keypoints and player positions [11]. Nie et al. [27] aim to learn a strong field representation by jointly predicting uniformly sampled grid points, line features, and area features. Inspired by predicting a dense grid of points [27], Chu et al. [8] formulate the task as an instance segmentation problem. We also apply instance segmentation [8] but on all individual field segments.

Initial Estimation: A grid of uniformly sampled and predicted points [8, 27] or predicted keypoints [11, 12] is the input for DLT (and variants) [18] to get usually a rough initial homography estimation. Segmented [23] or raw [32] images are used to directly predict the homography or to regress four points. Still, such approaches require annotated homography matrices for training [27]. Sharma et al. [31] develop a large synthetic dataset of camera poses, whereby Chen and Little [6] train a Siamese network to learn a representation of the respective segmentation mask and retrieve the nearest neighbor given an input mask. Sha et al. [30] use a much smaller database and consequently leave the refinement module to perform large non-affine transformations to the semantic input image.

Homography Refinement: Homography refinement is a crucial step in order to obtain a more accurate estimate, if necessary [8]. Previous approaches [6, 36] use the Lucas-Kanade algorithm [3], also in combination with spatial pyramids [16] with the assumption that the image transformation is small. To handle large non-affine transformations, the Spatial Transformer Network (STN) [21] was introduced in sports field registration. Refinement is performed during one feed-forward step [30] or by iteratively minimizing the difference between the input image and the initial estimation [23, 27].

Accessing Individual Camera Parameters: Carr et al. [5] leverage a gradient-based image alignment algorithm to estimate camera and lens distortion parameters, but the refinement is performed on the homography. A database of synthetic templates [6, 30] allows for direct access to the
camera pose as projective geometry is used to create template images. However, the smaller the database, the larger the reprojection error is without a refinement step. Despite the focus on homographies, it allows us to access individual camera parameters, at least with homography decomposition [11, 18]. Citraro et al. [11] decompose the initial estimated homography matrix to achieve temporal consistency and also apply a PoseNet [24] to regress translation and quaternion vectors.

3. TVCalib: Keypoint-less Calibration

After modeling the calibration object and camera model (Sec. 3.1), we propose the differentiable objective function (Sec. 3.2) that aims to approximate individual camera parameters given segment correspondences by iteratively minimizing the segment reprojection loss in 2D image space. Finally, we introduce its direct application, the 3D sports field registration (Sec. 3.3) and required segment localization (Sec. 3.4). The main workflow is summarized in Fig. 1.

3.1. Calibration Object & Camera Model

Given a calibration object (with known dimensions) that can be divided into individual labeled sub-objects of fundamental primitives (in this paper called segments) like points, lines, or point clouds, the aim is to predict the underlying camera parameters $\phi$ and potential lens distortion coefficients $\psi$ that minimize its reprojection error.

Modeling the Calibration Object: Line segments are defined in the parametric form $s_{\text{line}} = \{X_0 + \lambda X_1 | \lambda \in [0, 1]\}$ and point cloud segments as $s_{\text{pc}} = \{X_j | j = 1, \ldots, |s_{\text{pc}}|\}$. Without loss of generality, we define a labeled point segment as $s_{\text{point}} = X \in \mathbb{R}^3$, resulting in the traditional Perspective-n-Point (PnP) formulation where 2D-3D point correspondences are given. Finally, the calibration object is the composition of all individual segments per segment category $\mathcal{C}$: $\mathbb{S} = \bigcup_{\mathcal{C} \in \{\text{point, line, pc}\}} \{s_{\mathcal{C}}^{(1)}, s_{\mathcal{C}}^{(2)}, \ldots\}$

Modeling the Soccer Field: A soccer field is composed of lines and circle segments (modeled as point clouds), representing all field markings, goal posts, and crossbars. Please note that keypoint correspondences are not directly used in our approach, since all potential visible keypoints are part of line segments. Nevertheless, we do not intend to exclude the possible explicit use of them here beforehand. We follow the segment definitions of Cioppa et al. [10], but modify the central circle and split it into two parts from a heuristic in a post-processing step after semantic segmentation to induce context information. In case of a vertically oriented middle line, all points of the central circle that lie on the left are assigned to a sub-segment left, otherwise they are assigned to the sub-segment right.

Modeling the Pinhole Camera: We use the common pinhole camera model $P = KR[I - t] \in \mathbb{R}^{3 \times 4}$ parameterized with the intrinsics $K \in \mathbb{R}^{3 \times 3}$, which define the transformation from camera coordinates to image coordinates, and extrinsics $[R \in \mathbb{R}^{3 \times 3}, t \in \mathbb{R}^3]$, defining the camera pose transformation from the scene coordinates to the camera coordinates. We assume square pixels, zero skew and set the principal point to the center of the image. In place of predicting the focal length directly, i.e., the only unknown variable in $K$, we predict the Field of View (FoV) and transform the image coordinates to Normalized Device Coordinates (NDC) for numerical stability (Appx. A.1). Following Euler’s angles convention, the rotation matrix $R = R_z(\text{roll})R_x(\text{tilt})R_y(\text{pan})$ is the composition of individual rotation matrices, encoding the pan, tilt, and roll angles (in radians) of the camera base according to a defined reference axis system. Intrinsics and extrinsics are thus only parameterized by $\phi = (\text{FoV}, t, \text{pan}, \text{tilt}, \text{roll})$, and assume that $\pi_\phi : X \rightarrow x$ projects any scene coordinate $X \in \mathbb{R}^3$ to its respective image point $x \in \mathbb{R}^2$.

Relation to the Homography Matrix: If $X_\pi = 0.0$ then $P^{3 \times [1, 2, 4]} = KR^{3 \times [1, 2]}[I - t] = H \in \mathbb{R}^{3 \times 3}$ is the respective homography matrix only able to map all points lying on one plane. Appx. B describes how to approximate $\phi$ given a predicted $H$ only.

Lens Distortion: As we do not want to restrict to a specific lens distortion model $\psi$ (e.g., Brown [4]), we define $\text{distort}_\psi(x)$ that distorts a pixel $x$ and undistort for its inverse function. In case lens distortion coefficients are not known a priori, we assume that undistort is differentiable which enables the possibility to jointly optimize $\psi$ and $\phi$.

3.2. Segment Reprojection Loss

Perspective-n-Point (PnP) refers to the problem of estimating the camera pose (extrinsics) from a calibrated camera $K$ given n 2D-3D point correspondences. Geometric solvers for PnP or PnP(f), that also estimate the focal length, approximate the projection matrix $P$ through the geometric or algebraic reprojection error for $\text{argmin}_P d(x, \pi_P(X))$ where $d(x, \hat{x})$ is the Euclidean distance between two pixels. However, accurate correspondences are assumed to be known, the focal length in $K$ needs to be estimated, and there are some further requirements (e.g., minimum number of points, number of points that are allowed to be on one plane, etc.) need to be considered [18].

Instead, we aim to learn the underlying camera parameters $\phi$ (and potential lens distortion coefficients $\psi$) by minimizing the Euclidean distance between all reprojected segments and respective annotated (or predicted) pixels (see Sec. 3.4 for segment localization). Our segment reprojec-
tion loss is based on the Euclidean distance between annotated pixels with respective segment label and reprojected segments of the calibration object.

Let us consider a sample-dependent number of pixel annotations \( x^{(c)} \in \mathbb{R}^2 \times 2 \) for each (visible) segment label \( c \in \mathcal{S} \). For a respective line segment \( s_{\text{line}}^{(c)} \), the perpendicular distance to its respective reprojected line \( s_{\text{line}}^{(c)} = \{\pi_\phi(X_0^{(c)}) + \lambda \pi_\phi(X_1^{(c)}) | \lambda \in \mathbb{R}\} \) can be computed for each \( p \in x^{(c)} \):

\[
d(p, s_{\text{line}}) = \frac{|\text{det}((\pi_\phi(X_1) - \pi_\phi(X_0)); (\pi_\phi(X_0) - p))|}{|\pi_\phi(X_1) - \pi_\phi(X_0)|}
\]

and hence describes the point-line distance. The distance between a pixel \( p \in \mathbb{R}^2 \) and its corresponding reprojected point cloud \( \{s_{\text{pc}}^{(c)} | j = 1, \ldots, |s_{\text{pc}}^{(c)}|\} \) is the minimum Euclidean distance for each \( p \in x^{(c)} \). The mean distance over all annotated points \( x \) is taken to aggregate one segment \( c \). Finally, the segmentation reprojection loss function needs to be minimized where each segment contributes equally:

\[
L := \arg \min_{\phi, \psi} \sum_{c \in \mathcal{S}} d_{\text{mean}}(\text{undistort}_\psi(x^{(c)}), \pi_\phi(s^{(c)}))
\]

Please note that \( \pi \) in Eq. (2) represents the reprojection of an arbitrary segment \( \hat{s} = \pi_\phi(s) \) to the image to simplify the notation. Depending on the segment type, point\leftrightarrow point, point\leftrightarrow line, or point\leftrightarrow point-cloud distances are computed. Without lens distortion correction, \text{undistort} can be considered as identity function.

Implementation details: All computations (image projection and distance calculation) can be performed on tensor operations, which allows for more efficient computation and parallelization. The input dimension of annotated or predicted pixels for each segment category \( C \) (e.g., lines) is \( x_c \in \mathbb{R}^T \times S_c \times N_c \times 2 \), where \( N_c \) represents the number of selected pixels, \( S_c \) is the number of segments for the specific segment category, and \( T \) is an optional batch or temporal dimension. However, we need to pad the input if the number of provided pixels per segment differ, and remember its binary padding mask \( m_c \in \{0, 1\}^T \times S_c \times N_c \). To reproject the 3D object, all points are projected from the following input dimension per segment type \( x_{\text{line}} \in \mathbb{R}^T \times S_{\text{line}} \times 2 \times 3 \), \( x_{\text{pc}} \in \mathbb{R}^T \times S_p \times N_{pc} \times 3 \), and \( x_{\text{keypoint}} \in \mathbb{R}^T \times S_{\text{keypoint}} \times 1 \times 3 \). Where \( N_{pc} \) is the number of sampled 3D points for each point cloud. After distance calculation for each segment type, the distance of padded input pixels are set to zero according to the padding mask of each segment category \( m_c \), implying that the distance of non-visible segments is also set to zero. Aggregating the \( S \) and \( N \) dimension via sum and dividing by the number of actually provided pixels of the input is equivalent to Eq. (2), where each segment contributes equally.

3.3. Gradient-based Iterative Optimization

Given human annotations or a model (Sec. 3.4) that predicts pixel positions with corresponding segment label, one way is to directly optimize the proposed objective function (Eq. (2)) via gradient descent.

Initialization: We do not further encode the camera parameters nor modify the modeled pinhole camera (Sec. 3.1), but rather aim to predict all unknown variables \( \phi = \{\text{FoV}, \text{pan}, \text{tilt}, \text{roll}, t\} \) in a direct manner. However, it is beneficial to initialize an optimizer with an appropriate set of parameters. We introduce some prior information restricting possible camera ranges. Raw camera parameters are standardized to a zero mean and provided standard deviation. For uniformly distributed camera ranges \( U(a, b) \), we transform to a normal distribution \( N(\mu, \sigma) \), so that \( \sigma \) covers the 95% confidence interval, given \( \mu = a + (b - a)/2 \) and finally initialize with zeros. Roughly speaking, this initialization corresponds to the mean image, e.g., a central view of the calibration object.

Multiple Initialization: In case there is a large variance for some parameter, for instance, the camera location, it is reasonable to provide multiple sets of camera distributions. Suppose this information is a priori, for instance, the main broadcast camera. In that case, a user can select the correct set, or this information is known from shot boundary and shot type classification (later denoted as stacked). Otherwise, we propose to run the optimization with multiple candidates and the best result is taken automatically by selecting the one with minimum loss (\( \arg \min \)) according to Eq. (2).

Self-Verification: Self-verification aims to identify all images in which the model is unable to calibrate or estimate the homography. While other approaches use the mean point reprojection error (e.g., [27]) or verify geometrical constraints [11], we can directly reject all samples whose loss (Sec. 3.2) is below a threshold \( \tau \in \mathbb{R}^+ \). This user-defined threshold controls the trade-off between accuracy and completeness ratio and can be found empirically, e.g., by taking the best global result on a target metric for a dataset. This procedure might be necessary for invalid input images, e.g., out of camera distribution, erroneous semantic segmentation, or internal errors during optimization such as local minima.

3.4. Segment Localization & Point Selection

The output of any model for the segment localization which provides pixel annotations for each visible segment
given a raw input image can serve as input for the calibration module as well as manual annotations. We use the DeepLabV3 ResNet [7] (Residual Networks) to perform instance segmentation for each visible line or circle segment and do not directly predict appropriate pixels per segment. Pixel selection is then a post-processing step, aiming to select, for instance, at least two points for a line segment with maximum distance, best representing a line where we follow a non-differentiable implementation [26]. Ideal lines are sufficiently represented by two points, however, we have noticed more stable gradients if more than two points are selected. Further, we want to allow potential for lens distortion correction based on the extracted points which may show a curved polyline.

4. Experiments

The experimental setup including the baselines, metrics, datasets, and hyperparameters is introduced in Sec. 4.1. The results and comparisons to the state of the art are presented in Sec. 4.2. We conduct ablation studies for the proposed (1) segment localization, (2) self-verification, (3) multiple camera initialization, and (4) lens distortion (Sec. 4.3), while limitations are discussed in Sec. 4.4.

4.1. Experimental Setup

4.1.1 Baselines & State of the Art

Team sports such as soccer are played on an approximately planar field, hence many approaches assume a 2D area and use homography estimation [8, 27, 30, 32] to map all segments lying on this plane. To additionally estimate the camera pose and focal length, a reasonable approach is therefore the homography decomposition (see Appx. B for details) denoted as HDecomp.

Since in TV broadcasts of games like soccer or basketball, individual field segments are primarily visible, rather than keypoints, a suitable baseline is homography estimation via DLT from line segments [26]. Further, we compare to Chen and Little [6] for homography estimation. As their retrieval and refinement module solely relies on synthetic data, we can test different variants for camera parameter distributions during training [34]. For a fair comparison, we neglect the impact of the original segment localization by using ground-truth masks generated from the SN-Calib annotations or use the predicted masks from our segmentation model. As a second approach, we apply the official implementation from Jiang et al. [23]. Jiang et al. [23] and other recent approaches [8, 27, 30] rely on annotated homography matrices for training.

4.1.2 Datasets

SN-Calib dataset: The SoccerNetV3-Calibration dataset [10] consists of 20028 images taken from the SoccerNet [14] videos (500 matches) and covers more camera locations in addition to the main broadcast camera. An example setting may consist of two cameras that are placed also on the same tribune as the central broadcast camera, but are closer located to the side lines (main camera left and right). In addition, there are other cameras, e.g., behind the goal and inside the goal, or above the field (spider cam). We have manually annotated these camera locations used in this paper to get an overview. Table 1 summarizes the camera type distribution and number of images per split (train, validation, test) without stadium overlap. Cioppa et al. provide annotation for all segments of the soccer field [10], i.e., lines, circle segments, and goal posts. Each visible segment has at least two annotated positions optimally representing the segment (i.e., corner and border points) in form of a polyline.

WC14 dataset: The WC14 dataset [20] is the traditional benchmark for sports field registration in soccer and contains images from broadcast TV videos (only central main camera without large zoom) from the FIFA World Cup 2014 and the corresponding manually annotated homography matrices. We have additionally annotated the segments in the test split according to the guidelines in SN-Calib [10].

4.1.3 Metrics

The quality of estimated camera parameters or homography matrices can be evaluated both at 2D image space by measuring a reprojection error, and in world space by measuring a projection error. Accuracy@threshold [26]: The evaluation is based on the distance of the reprojection of each soccer field segment and the corresponding annotated polyline. Segments are reprojected from the predicted camera parameters \( \phi \) (and \( \psi \)) to the image from dense sampled points of the 3D model resulting in one polyline for each segment. A polyline
corresponding to a soccer field segment $s$ is detected as a true positive (TP), if the Euclidean distance between every point of the annotated polyline of segment $\tilde{s}$ and the reprojected polyline $\pi_{\phi}(s)$ is less than $t$ pixels: $\forall p \in \tilde{s}: d(p, \pi_{\phi}(s)) < t$. If the distance of one annotated point to its corresponding projected polyline is greater than $t$ pixels, this segment is counted as a false positive (FP), along with the projected polyline that does not appear in the annotations. Segments that are only present in the annotations are counted as false negatives (FN). Finally, the accuracy for a threshold of $t$ is given by: $\text{AC}@t = TP/(TP + FN + FP)$. If the camera calibration or the homography estimation may fail for some images, the Completeness Ratio (CR) measures the number of reprojection errors divided by the number of images of the dataset. Compound Score (CS): To summarize the above four scores, they are weighted as follows [26]:

$$CS := (1 - e^{-4CR}) \sum_{t \in [5, 10, 20], w \in [0.5, 0.35, 0.15]} w \text{AC}@t$$

Intersection over Union (IoU) [20]: The accuracy for homography estimation for sports fields is traditionally evaluated on the $\text{IoU}_{\text{part}}$ and $\text{IoU}_{\text{whole}}$ metrics that measure the projection error. They calculate the binary $\text{IoU}$ of the projected templates from predicted homography and a ground-truth homography in world (top view / bird view) space for the visible area (part) and the full (whole) area of the sports field, respectively. Due to the absence of ground-truth information like camera parameters, the evaluation can only be performed given annotated homography matrices [20] that are obtained from the visible sports field in the image (e.g., via DLT). Hence, projection correctness can be guaranteed only for the visible area and we prefer the usage of $\text{IoU}_{\text{part}}$ similar to Nie et al. [27].

4.1.4 Hyperparameters

Optimization: We use AdamW [25] with a learning rate of 0.05 and weight decay of 0.01 to optimize the camera parameters $\phi$ for 2000 steps using the one-cycle learning rate scheduling [33] with $p = 0.5$. These parameters were found on the SN-Calib-valid split through a visual exploration of qualitative examples. Calibration Object & Camera Parameter Distribution: Furthermore, we set the number of sampled points for each point cloud to $N_{\text{pc}} = 128$ ($0.45m$ point density for the central circle). We use a very coarse camera distribution (see Appx. A.2) of the main camera center and apply it to all datasets. Segment Localization: The training data are derived from the provided annotations of the SN-Calib-train dataset. For training details we refer to Appx. C. Please recall that the expected dimension for each segment category $C$ is $N_{c} \in \mathbb{R}^{7 \times S_{c} \times N_{C} \times 2}$. We set $|N_{\text{line}}| = 4$ and $|N_{\text{pc}}| = 8$ following initial considera-

4.2. Results & Comparison to State of the Art

Previous approaches focus on the (1) main camera center and (2) homography estimation. Hence, we (1) compare on the subset of SN-Calib-test and (2) measure both the camera calibration performance induced by the predicted camera parameters and the homography estimation.

Reprojection Error for Camera Calibration: This task represents the main task of estimating individual camera parameters $\phi$ where the reprojection error (AC@t) induced by $\phi$ is evaluated. The results on the test splits on SN-Calib-center and WC14-test are presented in Table 2 (top) and Table 3, respectively.

Pred vs. Ground Truth (GT) Segmentation: If the same ground-truth segmentation is used as input, our method outperforms the best variant from Chen and Little [6] ($\text{IoU}_{\text{FoV}} + \text{IoU}_{\text{BG}}$ [34]) and the baseline on both datasets.

Self-Verification: The homography decomposition also contains a kind of self-verification resulting in a higher reprojection accuracy (AC@t) but lower completeness ratio (CR), as shown in Tables 2 and 3. Hence, we can compare these approaches with our results after self-verification of TVCalib. Superior results are achieved for all variants of segmentation and on both datasets.

Reprojection Error for Homography Estimation: To investigate whether the quality of the homography estimation or the decomposition are the reason for the results, we examine the plain performance of the homography estimation and thus exclude the impact of the homography decomposition. We measure the same metrics, but only map all segments lying on one plane, i.e., ignore goal posts and crossbars. The results for the estimated as well as the ground-truth homography matrices are presented in Table 2 (bottom) and Table 4.

Influence of the Homography Decomposition: Compared to the reprojection error for the calibration task, noticeably better results are achieved indicating that the decomposi-
tion introduces additional errors. Based on the per-segment accuracy, we found that in particular a larger projection error is frequently visible for goal segments since the height information is missing but not the only reason for higher errors (e.g., DLT Lines with and without HDecomp).

Pred vs. GT Segmentation: Similar to the evaluation of camera calibration performance, superior results are
Table 2: Results on SN-Calib-test-center only evaluating where the main camera center is shown (1454 images). When evaluating the homography, all segments not lying one the plane (goal posts and crossbars) are ignored.

Table 3: Evaluating the reprojection error induced by the camera parameters (φ) on WC14-test dataset (186 images).

Table 4: Evaluating the homography estimation on WC14-test: IoU\textsubscript{part} compares the projection error (top view) using annotated homography matrices (H [20]). Grayed out: Results taken from the respective paper.

4.3. Ablation Studies

Impact of Segment Localization (Pred vs. GT): TVCalib achieves very similar results compared to the reproduced approaches and other state-of-the-art approaches without performing training or fine-tuning on this dataset. The reprojection error measured via AC@t from the annotated homographies H is comparable with our results (Table 4), but not ideal, demonstrating bias on the IoU metrics since H is used to evaluate the projection error.

Choice of the Self-Verification Parameter: Please recall that τ is a user-defined threshold able to reject images based on the reprojection loss. For simplicity, we have set this value once globally based on the maximum CS on SN-Calib-valid-center (predicted segment localization), but the optimal value can be chosen for each dataset and configuration individually or specified manually. This value is roughly valid across multiple datasets, camera distributions, and splits (see Fig. 2). The projection performance is shown in Fig. 3 for multiple configurations of TVCalib by varying this parameter. In general, the more τ is restricted, the less the completeness ratio decreases, with increasing accuracy that at some point saturates.
Multiple Initialization: As our solution aims to optimize the camera parameters for multiple camera locations (center, left, right), (1) the question arises whether one initialization (center) is sufficient or multiple initialization (one per camera location) are preferred, and (2), if the camera position is known a priori, one variant is to use only the respective initialization and for this experiment to stack the results (stacked). The other variant utilizes the optimization from multiple initializations and takes the best result (argmin). As shown in Fig. 3, initializing from three camera positions (argmin and stacked) is noticeably better than using only one initialization (center), and selecting the best result (argmin) is slightly better than knowing the camera type in advance (stacked). Due to the iterative optimization process, the ability to start from several locations enables the chance to find better minima.

Lens Distortion: The results when camera and radial lens distortion parameters were learned jointly are presented and discussed in Appx. D. In summary, results can be improved at AC@5 for samples where radial lens distortion is visible.

4.4. Limitations

Despite strong results, for a small fraction of given ground-truth segment annotations, some samples are rejected. This is mainly caused by local minima due to the nature of gradient-based iterative optimization [1]. Related to the camera initialization, we have not investigated any cameras other than those on the main tribune. The TVCalib approach relies on an accurate segment localization, but no regularization term is included that allows for outliers. Finally, jointly learning lens distortion coefficients has not been deeply investigated.

5. Conclusions

We have presented an effective solution to learn individual camera parameters from a calibration object that is modeled by point, line, and point cloud segments. Furthermore, we have successfully demonstrated its direct application to 3D sports field registration in soccer broadcast videos. In the target task of 3D as well as for 2D sports field registration in terms of the image reprojection error, our method has achieved superior results compared to two state-of-the-art approaches [6, 23] for 2D sports field registration in terms of the image reprojection error.

Future work could investigate the integration of temporal consistency and associated speedup, the application to other sports, and finally the incorporation into a deep neural network to estimate the camera parameters in one feed-forward step or full end-to-end learning.

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