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A Self-identifying Checkerboard-like Pattern for Camera Calibration

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Abstract: This paper proposes a new type of planar pattern for camera calibration featuring its checkerboard-like structure and self-identity. White and black blocks are arranged by a novel method to ensure the uniqueness of each local pattern, and meanwhile maintain all checkerboard corners. The pattern is generated by combining identification units based on a random search strategy. Positions of local patterns can be acquired by searching the global pattern, achieving the benefit of self-identity. Because of the checkerboard-like structure, no burden is introduced in sampling compared to traditional calibrations. Experimental results show the effectiveness of the proposed calibration method. The conceived pattern is especially suitable for the calibration of multi-camera system with limited overlapping scope.

Key Words: Camera calibration, pattern, self-identity, checkerboard-like

1 Introduction

Calibration is a critical process for multi-camera systems before applications such as measurement, modeling and visual odometry. The measurement accuracy of multi-camera systems highly depends on the accuracy of calibration. Multi-camera calibration requires extracting and matching features in the views of different cameras. The more matched feature pairs, the better quality of the calibration result. Therefore, a large variety of calibration targets and methods have been designed to facilitate the extracting and matching process of features.

A calibration target can be classified according to its dimension [1]. Calibration with a 3D target, which usually contains two or three orthogonal planes, shows satisfying efficiency and accuracy, while the device is expensive and the process is complicated. Calibration with 0D features refers self-calibration and method which records a video of a moving bright spot for calibration [2]. The feasibility of 1D calibration target has also been suggested available [1]. 2D calibration target is the most prevalent calibration target on account of its huge amount of features and convenience in implementation.

To correctly match hundreds of feature points among views, a fundamental question is that how the feature points can be distinguished from each other. Existing settlements of calibration patterns brings drawbacks in different aspects respectively. Checkerboard and circular dots are popular patterns in practice since plenty of solutions are available for feature extraction such as corner, edge, centroids and conic fitting. Perspective bias and distortion bias might have different effects on the calibrations when applying these patterns [3], so each pattern has its suitable application scenario. Some variants of these two patterns are proposed. The most popular calibration method [4] used a colored square matrix. Concentric circles, which shares similar feature detection process with circular dots pattern, could increase the accuracy and robustness of feature localization [5]. The patterns mentioned above are all organized by repeating same elements and arranging them in a matrix. The simple structure ensures an easy manufacturing. Their drawback is that different features all looks the same, causing the difficulty in matching features in different views, especially when the calibration board are partial occluded in the field of views.

To distinguish features from each other, feature localization shall be adopted. An effective way is adding some constraints to the pattern arrangement and distinguish the board orientation, the positions of features on the target is then inferred in software toolbox. The calibration toolbox in Matlab requires the row number of checkerboard to be even and the column number of checkerboard to be odd. Asymmetrical circle dots pattern was applied to avoid discrimination in orientation detection [6]. The problem of such kinds of pattern is that features can be localized only if the whole calibration board is in the view, which is sometimes impractical to satisfy when the overlapping field is rather limited. Another way to provide relative position information of features is adding several markers on pattern directly. Checkerboard pattern with three markers on it was proposed to indicate the orientation of the calibration board [7]. Such modification has also been applied to other kinds of patterns, such as square matrix pattern [1, 8, 9], circular pattern [10], and concentric circle pattern [5, 11]. However, these methods still require the full presence of the calibration board.

To distinguish features from each other when only part of calibration pattern appears in the field of view (so called "self-identifying" ability), some researches introduced visual fiducial patterns, which was initially designed for augmented reality system or robot localizing system, into the

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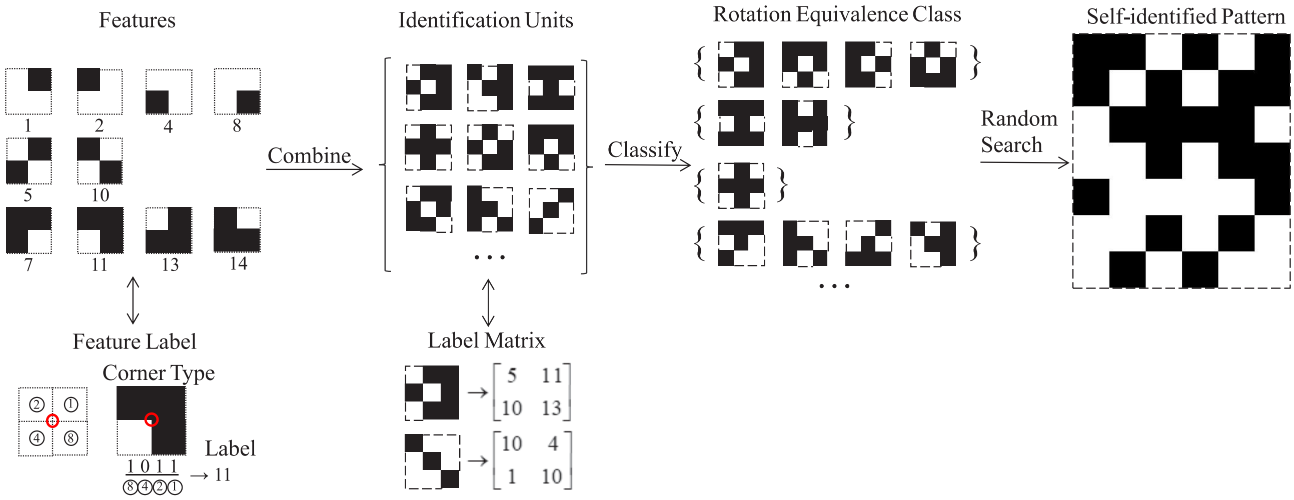

Fig. 1: Calibration pattern design procedure. Here an example of a 7×6 pattern based on 3×3 identification units is shown.

design of calibration patterns. Popular AprilTags was adapted to a calibration target [12, 13], which utilized the corners of a visual fiducial as features and the fiducial itself indicated positions of features. Similarly, CALTag has also used as markers for every feature [14]. ArUco and ChArUco have already been standard calibration patterns for many calibration toolboxes such as OpenCV and Kalibr, which follow the same principle. Fiducials based on circle dots or concentric circles have appeared [15, 16]. A disadvantage of these methods is that visual fiducials require much higher solution to discriminate, thus more area is accounted for visual fiducials and less features appear in the view.

Much effort has been made to increase the identity of each feature in other ways. A checkerboard-like pattern was designed to have different cross ratio of adjacent intervals everywhere [17], and the image of small portion of the pattern would find its corresponding position easily. A more direct way to generate patterns is summing multi-scale random points [18], ensuring uniqueness of local patterns and providing sufficient features. Multi-scale feature is designed to accommodate cameras at different zooming levels. Solutions include generating points by summing features in different scales [18]. The concept of fractal was also borrowed in pattern design [19, 20]. These methods set features in random positions, increasing the difficulty of localizing features in calibrations.

This paper proposes a novel pattern with self-identify property and checkerboard-like structure. Compared to existing self-identifying patterns, we make the following contributions:

- The identifying information is fused into checkerboard instead of taking extra place like fiducial markers, thus the required resolutions for corners detection and feature positioning are the same. It means no burden is introduced in sampling compared to traditional calibrations.
- The pattern provides exactly the same corner positions with traditional checkerboard, thus existing calibration toolboxes can be used without much modifications.

The rest of this paper is organized as follows. In Section 2, the generation algorithms of the proposed pattern are described. Feature positioning methods for the proposed pattern are also provided as explained in Section 3 and tested in Section 4. Finally, the conclusion and future work are given in Section 5.

2 Calibration Pattern

The proposed pattern is based on checkerboard-like structure, then designing the pattern is to judge each block of the grid is whether black or white. The design of calibration pattern follows the procedure shown in Fig. 1. The pattern is designed to achieve two prominent goals as follows:

- The pattern should be self-identifying so that features can be easily recognized.
- Each grid point should be maintained as a corner feature.

2.1 Adopted Features

Features are designed to be the grid points and should be recognized based on the pixels nearby. While maintaining features as corners, corner type informations are used to differ features. There are 10 possible features totally. Features are coded with labels to represent different corner types, and the code rule is shown in Fig. 1. Labels should not be the integer multiple of three, or the feature it indicates is not a corner. Choosing labels from these 10 available options for all the grid points will promise them to be detected as corners.

2.2 Pattern Structure

While making a larger pattern to provide more features in a single image, it is obvious that 10 corner types are far beyond adequate to distinguish hundreds of features, thus other basic unit should be adopted for identification. A small grid of features, which is a combination of several features, has more different types. The local area contains several features is referred as an identification unit. Fig. 1 shows 3×3 identification units which contain 4 features, and the labels of those features can be represented in a matrix. Such an identification unit have enough types to be arranged at the different parts of the calibration pattern.

The structure is explained as follows. Any local area with the size of the identification unit in the calibration pattern is regarded as an identification unit, and all the identification units appeared in the calibration are different to each other. Additionally, to make all the identification units recognizable when the pattern is rotated, all the identification units together with all their rotations should be different to each other.

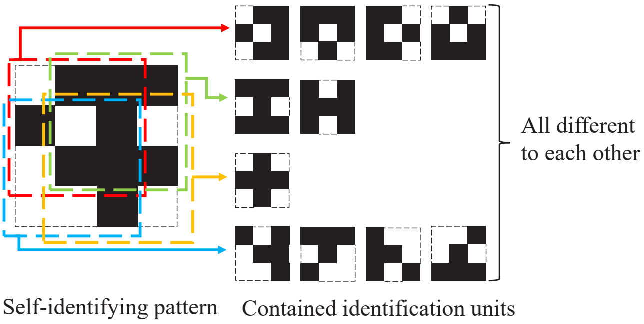

Fig. 2: A 4×4 calibration pattern based on 3×3 identification unit.

An illustrative example is shown in Fig. 2. Here the size of the identification units is 3×3 and a self-identifying calibration pattern is depicted in the left. Any 3×3 local region in the calibration pattern in any rotate angle is unique, and the position and orientation can easily be recovered by comparing the selected local identification unit with the whole origin pattern. Such structure promises the self-identity and rotation invariance of the calibration pattern. In addition, any part of the proposed pattern still holds the same properties, implying that the proposed pattern can easily be tailored to meet the requirement in practice.

2.3 Estimation of The Maximum Pattern Size

Since the tailored pattern maintains all the properties, small patterns are derived naturally once a larger pattern is required, so the largest pattern size worth being investigated. When the size of the local identification unit is chosen, the quantity of possible identification unit is finite, therefore there exists a maximum size of the designed pattern theoretically. A rough estimation of an upper bound could be found with the help of computer.

The quantity of possible identification units is firstly considered. The number of identification unit types cannot count by the permutation and combination since not all the possible point pairs could be adjacent. For example, features with label 5 cannot be situated in the right of features with label 2. Here we made a computer program to list all the possible local identification units with given size. Some results are listed in Table 1.

Table 1: The quantity of possible identification unit

Size	Identification units	Rotation equivalence classes
2×2	10	3
3×3	94	30
4×4	1460	374
5×5	43870	11068

For an identification unit set, rotation is an equivalence relation on it, so the identification unit set can be divided into many equivalence classes. The third column of Table 1 shows the number of the equivalence classes of a specified identification unit. The total number of identification units in the designed pattern should be less than the number of the equivalence class. For example, one of the largest self-identifying patterns based on 3×3 identification units is the self-identifying pattern shown in Fig. 1, which contains and only contains one identification unit from all thirty rotation equivalence classes.

2.4 Pattern Generation

Since theoretical analysis of the proposed pattern has not appeared, the pattern is generated by random search. Each identification unit is chosen in every horizontal line from left to right in order. The chosen identification unit would reduce the available options of unchosen ones. On one hand, when choosing a new identification unit, the selected one should be different to all the previous chosen identification units and their rotating situations. On the other hand, the newly chosen identification unit must share the same content with previously chosen identification units in their overlapping area. These may lead to the situation that no identification unit is appropriate to choose in some positions, and the operations to deal with it is to give up and generate again from the beginning. The generation process of the sample pattern relevant to Fig. 2 is illustrated in Fig. 3.

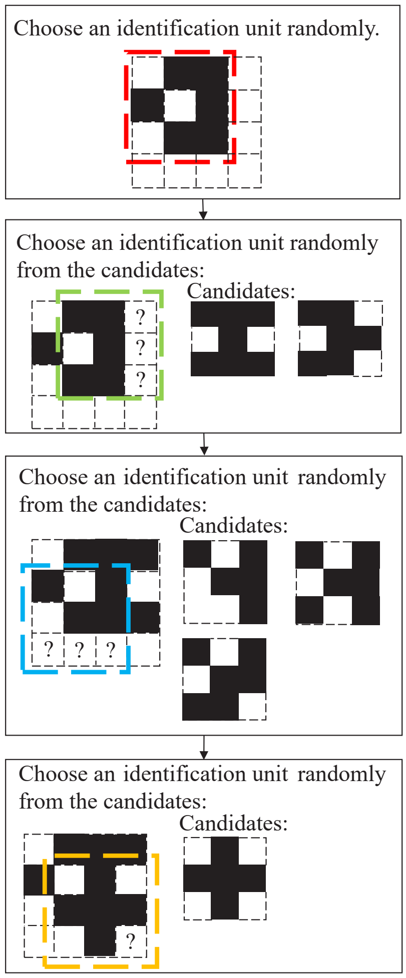

Fig. 3: Generation process of the pattern in Fig. 2.

The strategy described above is useless when generating a relatively large pattern. For identification units with 4×4 size, random search strategy is effective to generate calibration patterns less than 11×11. To obtain larger pattern, an available method is to generate a small pattern in random search strategy first, and then add rows and columns separately. To do so a 10×10 pattern based on 4×4 identification units is expanded to the size of 14×14. Here two 14×14 patterns based on 4×4 identification units and a 20×20 pattern based on 5×5 identification units have already been generated, as shown in Fig. 4. Note that the size of the pattern can be tailored as needed for any part of the pattern inherits all the properties mentioned before.

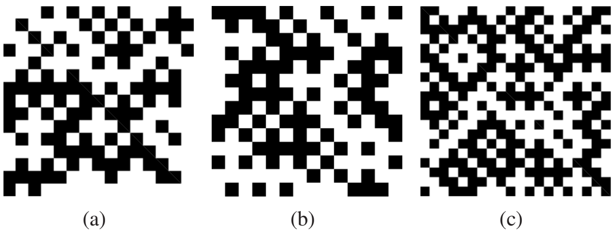

Fig. 4: Three available patterns generated in random strategy based on different identification unit size. (a) and (b) are two 14×14 patterns based on 4×4 identification units and (c) is a 20×20 pattern based on 5×5 identification units.

3 Feature Positioning

The processing of the captured images contains three steps: corner detection, label extraction, and feature points localization. Most existing corner detecting methods are suitable for the task, and this section focuses on label extraction and feature points localization which are related to the intrinsic property of the pattern.

3.1 Label Extraction

To detect the label of each features, we inspect the gray value of the neighbors in eight directions. Fig. 5 shows the whole process, and the pattern used here is Fig. 4(b). As shown in Fig. 5, two labels can be acquired on directions ⑧⑥④② and directions ⑦⑤③①. One of the two directions is closer to the edge, and labels on this direction tend to be wrong. The two labels of every feature are to gather statistics to examine on which directions produces less wrong labels, then labels on chosen direction is adopted. The criterion to examine if a label is right is to check if a label is the integer multiple of three.

3.2 Feature Point Localization

After getting the labels of all the features, an identification unit is chosen to match the original pattern. The detected labels of an identification unit cannot be utilized directly for matching as two factors affected its orientation. First, the calibration pattern may be presented rotationally. Second, the detecting orientation of labels may not be aligned with the calibration pattern. When dealing with the detected labels, detecting orientation should be firstly aligned with the pattern by checking their feasibility of forming a legal identification unit, then aligned labels, with rotationally uniqueness, can be discovered in the pattern and the positions of the identification units and all the features are gotten. An illustration is showed in Fig. 6.

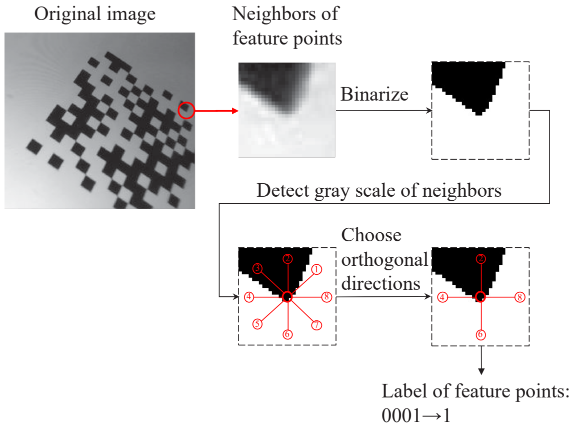

Fig. 5: Process of determining the labels of features.

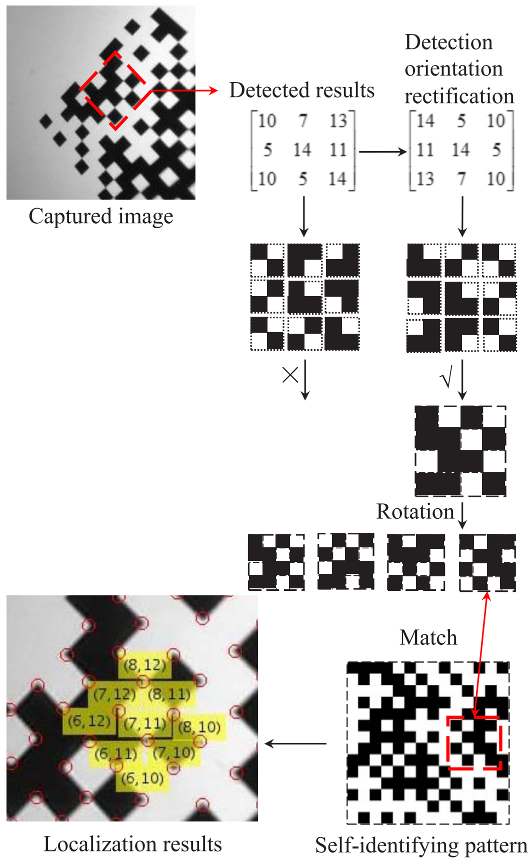

Fig. 6: Feature points localization procedure.

4 Experiment in Multi-camera Calibration

In this section we describe the label extraction and feature points localization in a multi-camera system calibration experiment. Before label extraction, Harris corner detection was utilized to find features and Matlab calibration toolbox was used to remove noises and corners belong to other objects. After feature point localization, Matlab calibration toolbox which is designed for checkerboard was also directly use for calibration. With the proposed pattern, photos which only captured part of the pattern could be used.

4.1 System Description

The multi-camera system was composed of six endoscopes fixed in a bundle. The diameter of each endoscope is 3 mm, and the baseline of two cameras ranges from 4 mm to 9 mm, thus endoscopes often capture images without a complete pattern. Much effort should be made on adjusting the position of calibration target to be fully captured in views when using traditional calibration boards. The multi-camera system is shown in Fig. 7. The calibration pattern was shown on a smart phone screen inspired by [21]. Fig. 4(b) was used in experiment.

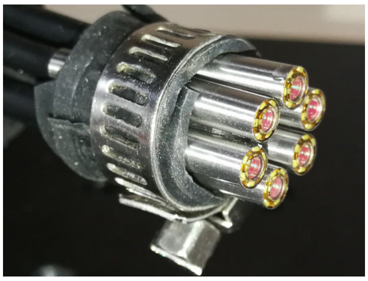

Fig. 7: The multi-camera system for calibration.

4.2 Positioning Result

The results are shown in Fig. 8, where features appeared in the view were correctly extracted and localized.

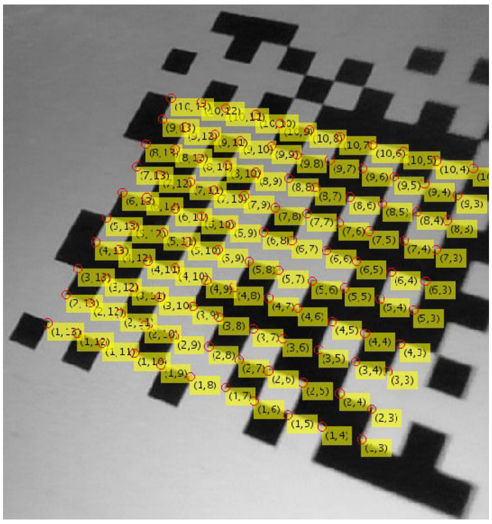

Fig. 8: Features positioning results of a captured image.

While calibrating multi-camera systems, the features appeared in views of both cameras were used in later calibration, which enables the calibration to be conducted with current popular calibration toolboxes under a circumstance of limited overlapping of scope.

5 Conclusions and Future Work

In this paper, we have proposed a new type of plannar calibration pattern with self-identity property and checkerboard-like structure. More specifically, the pattern is generated by combining identification units based on a random search strategy. Self-identity is achieved by ensuring the uniqueness of every local pattern, thus the position of any observed identification unit can be calculated by matching. Compared to existing self-identifying patterns, the proposed pattern maintains a checkerboard-like structure, thus no burden is introduced along with the valuable properties. Experimental results indicate that feature coordinates are still available when the proposed pattern is not fully captured, as illustrated by the calibration of a multi-camera system with limited overlapping scopes.

High complexity is one of limitations of the pattern generating method, which is time-consuming at large pattern generation. Another limitation is that supremum of the pattern size still remains unknown with a given identification unit size. We will address these problems in our future work.

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