Abstract

We describe an approach to characterize the signatures generated by walking humans in spatio-temporal domain. To describe the computational model for this periodic pattern, we take the mathematical theory of Geometry Group Theory, which is widely used in crystallographic structure research. Both empirical and theoretical analysis prove that spatio-temporal helical patterns generated by legs belong to the Frieze Groups because they can be characterized by a repetitive motif along the direction of walking. The theory is applied to an automatic detection-and-tracking system capable of counting heads and handling occlusion by recognizing such patterns. Experimental results for videos acquired from both static and moving ground sensors are presented. Our algorithm demonstrates robustness to non-rigid human deformation as well as background clutter.

1 Introduction

1.1 Motivation

Human gait has recently become one of the most active research areas in computer vision. The key issue is modeling the shape deformation. In this paper, we address an automatic method for detecting periodic patterns generated by a human walking motion in spatio-temporal slices. Periodic pattern are widely researched in texture and crystal structure analysis using Group Theory [2]. As is well know, seven Frieze Groups describe all patterns generated by translation along one dimension, seventeen Wallpaper Groups describe all patterns generated by two linearly independent translations, and two hundred and thirty Space Groups describe regular crystal patterns generated by three linearly independent translations [5]. Experimentally speaking, human gait repeats itself during walking and hence generates a periodic motion. The bipedal movement of two legs exhibits symmetry.

Following Klein’s Erlangen work [9] we look for properties preserved by the symmetry in human motion. The proposed computational approach includes three main components: 1) Recover the underlying property of human gait pattern in spatio-temporal domain using Group Theory; 2) Detect the symmetric group in real images; 3) Identify a representative motif that perceptually characterizes the gait pattern for each individual.

1.2 Related Work

The review by Gavrila [3] and Liang [6] categorized human motion analysis according to whether an explicit shape model was used and the dimensionality of the model space. For example, Little [7] and Liu et al [8] used a Discrete Fourier Transform (DFT) to measure pixel oscillations. Niyogi and Adelson [10] analyzed the periodic patterns and used them to estimate gait parameters. Ran [11] et al also proposed a MPGA fitting method followed by a PLL for continuous classification.

Because of the upright pose and piece-wise translational global body displacement during human walk, considering in spatio-temporal domain is more effective than in image space. We also observe strong periodic patterns like those in texture or crystal structure. One most related work is [13] by Liu et al. The authors project silhouettes into horizontal and vertical axis to generate patterns and explore variations with respect to viewing direction. In contrary, our method directly considers gait with the global translation in the original domain. The contributions are twofold. First we explicitly integrate the temporal information into our pattern model. Second we provide a method to directly solve several surveillance applications in spatio-temporal domain.

This paper is structured as follows. Section 2 presents the analysis of periodic motion signature and its relationship to Frieze Groups. Section 3 discusses the extraction of the signatures. Section 4 discusses applications ranging from human detection, head counting in surveillance supported by results. Section 5 summarize our approach.
2 Periodic Motion Signature

2.1 Frieze Groups

We give a brief overview for Geometric Group Theory [9]. It was studied extensively in several ancient civilizations and in particular, the Greeks used it to lay the foundations of our modern "axiomatic" treatment of mathematics. In this paper, we are more interested in the geometrical pattern group in 2D spatio-temporal slices. A Frieze Group, as in Fig. 1 is an infinite discrete symmetry group for a pattern on a strip in 2D domain. There are seven different Frieze Groups [2]. What interests us most in Frieze Groups is the fact that it necessarily contains translations and may contain glide reflections, which is a good representation for human movement.

2.2 Gait Signature

Researchers try to model the kinematics and dynamics of various human body parts. There has been much work on generating gait for animation [12]. What interests us are the patterns generated by human or animal legs in horizontal planes parallel to their moving direction. The proposed gait model here is a twin-pendulum model composed of two identical, out-of-phase pendular oscillating at a constant angular speed from a common point. Fig. 2 exhibiting that the periodic patterns of this model having symmetry groups at horizontal planes. This result shows that human gait is bilaterally symmetric and the potential to be effective for detection pedestrians over time.

In the above described hip-to-toe motion, each leg is modeled as an arm of the twin-pendulum with equal length and a uniform angular swing speed \( \theta \) with period \( T \) and a translation speed \( v \). The generated gait signatures are shown in the second row of Fig 2 when the twin pendulum is translating across the image from left to right. The slices generated by the 'legs' contain twisted patterns. We realize that they contain different symmetries such as reflection symmetry along horizontal and vertical axes, \( 180^\circ \) rotation. Denote the pattern at height \( z \) as \( S_z(t) \) where \( t = 1, 2...T \). Since the 'legs' are of unit width, the signature at time \( t \) could be represented by only two points.

\[
S_z(t) = \{P_1, P_2\} = \{(z \tan \theta(t) + v \ast t, t), (-z \tan \theta(t) + v \ast t, t)\} \tag{1}
\]

Hence any pattern \( S_z \) at height \( z \) has periodicity \( \pi \), or \( T/2 \) and a horizontal symmetry along line \( (v \ast t, t) \) in the X-t image at height \( z \).

Actual human gait is more complicated than discussed above. But they do share some basic kinematic and symmetrical features. In order to find the Frieze Group it belongs to, we incorporate the bio-mechanical priori knowledge, into the gait animator for the lower human body. From the symmetric pendulum example, we know that the helical pattern are identical in terms of a scale factor and hence share the same Frieze Groups category. Does this still hold for real gait? We find that the spatio-temporal helical patterns generated by hip-to-toe gait articulation belong to a Frieze Group.

Given a set of gait configuration \( \Theta = \{\theta_r, \theta_l\} \). The articulation parameter \( \theta_l \) and \( \theta_r \) must be identical with a \( \pi/2 \) phase difference due to the cyclic property, i.e.:

\[
\theta_l(t) = \theta_r(t - T/2) \tag{2}
\]

Also we have the following from periodicity:

\[
\theta_l(t) = \theta_l(t + T), \theta_r(t) = \theta_r(t + T) \tag{3}
\]

We focus at the pattern generated by two legs at a given height \( z \). Articulation at time \( t \) will have two points at the \( t-th \) row in plane \( Z = z \). They can be represented as

\[
S_z = \bigcup_{t=1}^{T} \Theta(t) \bigcap \{Z = z\}
\]

\[
= \left( \bigcup_{t=1}^{T} \theta_l(t) \bigcap \{Z = z\} \right) \bigcup \left( \bigcup_{t=1}^{T} \theta_r(t) \bigcap \{Z = z\} \right) \tag{4}
\]
For a given \( t \), we have

\[
S_z(t) = (\theta_l(t) \cap \{Z = z\}) \cup (\theta_r(t) \cap \{Z = z\})
\]

\[
= (\theta_l(t - T/2) \cap \{Z = z\}) \cup (\theta_r(t - T/2) \cap \{Z = z\})
\]

\[
= (\theta_l(t + T/2) \cap \{Z = z\}) \cup (\theta_r(t + T/2) \cap \{Z = z\})
\]

(5)

Hence the pattern belongs to a Frieze group with a period of \( T/2 \) and a 1D translation vector. Further more, if we assume that the timing of each single leg also has a symmetry according to the middle stance when two legs are both contacting ground, we can derive a reflectional symmetry by a similar approach. These two nice features help us to verify the existence of gait patterns in slices around limbs.

3 Motion Signature Extraction

The key issue in periodic pattern extraction is whether the 2D lattice can be correctly extracted. The same issue exists for gait pattern extraction. Previous work on lattice detection can be divided into feature based and correlation based approaches [13]. The first one extract features and organize them based on visual similarity. The benefits of this approach are the ability to detect small regions of a repeating pattern within a larger image. The drawback is the need for a pattern with distinct corner/edge/contour features. The other approach to detecting global pattern repetition is to use autocorrelation, the Fourier Transform, or periodicity measures defined over co-occurrence matrices. These approaches work for any intensity image but requires that a single periodic pattern occupies a large portion of the image, limiting the approach to analysis of patterns that occupy part of the image.

In our approach, we take a new method to overcome the disadvantages in both of the methods since the lattice here is a 1D band. We first apply a Harris corner detector [4] for the whole slice, then a Hough line detector is used to cluster the corners into lines after sub-sampling the original feature images. We show in Fig. 3 how the proposed algorithm can be used to automatically specify orientation for gait periodic pattern.

After detecting bands of interest in a X-t images, we apply a masked autocorrelation for each band. Local peaks are extracted within a preset supporting neighborhood (5*5 in our case) representing the lattice of that pattern. The last step is to verify the undergoing symmetry(s) to decide the existence of a human gait pattern in each motifs. We take an approach for each individual pattern as below:

1. For bands 1, 2,..., N, do the following:

2. Test for the existence of translation symmetry in one band: Find local peaks to obtain the 1D lattice. Compute the normalized distance between peaks. If the variance \( \sigma_1 \) for those distances falls in a preset threshold, a translational symmetry is said to exist in this band. Otherwise go to the next band.

3. Estimate a mean tile by averaging in this band.

4. Test for the existence of reflection symmetry: obtain a reflected tile by rotating \( \pi \). Compute the normalized sum of residual error. If the error \( \sigma_2 \) falls in a preset threshold, a gait pattern symmetry is said to exist in this band.

4 Applications

4.1 Detection

A direct application is in the detection of pedestrians in spatio-temporal images. Fig. 3 shows the typical detection results. In all cases, the method detects the correct periodic pattern and locates pedestrians in the sequences.

Figure 3. Color/gray video: 1st row: original X-t slice containing 3 objects; 2nd row: detected bands with partitioning into tiles; 3rd row: verified gait pattern; 4th row: corresponding objects in images.

If we use a range sensor or an IR sensor, the target will have almost uniform response because of range or body temperature. A similar result is given in Fig. 4. We also present the ROC curves in Fig. 5 for the UMD that has 350 pedestrian clips to statistically evaluate our detector. Compared to the results from a shape based detector, we obtain higher performance in terms of detection rate at the same false negative rate. This is due to the exploration of temporal symmetrical motion coherence.

4.2 Counting people

Vision-based counting of humans aims to extract the number of people present in an observed area. We are aiming at getting the number of pedestrians for a period of time rather than individual frames. But the traditional methods requires tracking or registration, which is a very challenging
problem due to occlusion and clutter. Another solution is to put the camera at the top of the building such that the task of counting people becomes one as counting heads. We take an alternative idea: counting legs. The camera, or range sensor, is located slightly higher than the ground and looks at the height where human legs will pass. Thus the human counting task becomes one of counting legs and the number of pedestrians is the number of the detected periodic helical patterns at the specific horizontal plane.

In the right image of Fig. 5, our method has achieved 95 percent detection rate with a false alarm rate less than 5 percent. The advantage lies in the inherited consideration of spatio-coherence of human gait. It directly finds pedestrians in videos without relying on any tracking module.

5 Conclusion

The articulation of pedestrian gait generates a repetitive pattern with a 1D translation vector decided by the body movement speed, which is represented by Frieze Groups. The proposed algorithm localizes the pattern in layered X-t slices and is applied to several surveillance applications such as detection, counting heads and occlusion handling. The experimental results demonstrate the effectiveness of the proposed method.

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References