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Population ecology

A tiger cannot change its stripes: using a three-dimensional model to match images of living tigers and tiger skins

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The tiger is one of many species in which individuals can be identified by surface patterns. Camera traps can be used to record individual tigers moving over an array of locations and provide data for monitoring and studying populations and devising conservation strategies. We suggest using a combination of algorithms to calculate similarity scores between pattern samples scanned from the images to automate the search for a match to a new image. We show how using a three-dimensional surface model of a tiger to scan the pattern samples allows comparison of images that differ widely in camera angles and body posture. The software, which is free to download, considerably reduces the effort required to maintain an image catalogue and we suggest it could be used to trace the origin of a tiger skin by searching a central database of living tigers' images for matches to an image of the skin.

Keywords: tiger; camera trap; pattern matching

1. INTRODUCTION

Camera traps are being used to monitor tiger numbers in Asia's remaining forests (Karanth *et al.* 2004, 2006). The traps detect and photograph animals moving along the forest tracks. Non-occluded sections of their coat patterns can be used to individually identify the tigers photographed. The resulting individual 'capture histories' are used in capture–recapture models (Williams *et al.* 2002) to estimate population size and other parameters relevant to planning and evaluation of conservation measures: population density; survival; recruitment; and temporary and permanent emigration (Karanth *et al.* 2006). The proportion of surviving wild tiger populations represented in photographic identification (photo-id) catalogues is therefore increasing and is set to increase further as imaging technology improves.

Where populations are small or highly fragmented, new images can be compared by eye with existing ones to identify new individuals and record where and when each was photographed. But as the photo-id catalogue grows with population turnover and immigration from adjacent sites, the effort required to search the entire catalogue for matches to each new image becomes excessive. The number of visual comparisons required can be reduced substantially by calculating similarity scores between each new image and the images by which existing individuals are represented in the catalogue. Visual comparisons can then be restricted to those individuals for which the maximum score exceeds a threshold value, as exemplified by the work of Kelly (2001) for cheetahs and Karlsson *et al.* (2005) for grey seals.

Camera trap images of tigers are characterized by a wide range of camera angles and body posture. To allow similarity scores to be calculated between such images, we developed a three-dimensional surface model of a tiger. The software, first developed for matching images of grey seals (Hiby & Lovell 1990), fits the model to each new image and scans the stripe pattern from the region of the image lying beneath a predefined region of the model, so that the resulting pattern sample is largely unaffected by camera angle and body posture. A pattern comparison algorithm then calculates similarity scores between the new and existing pattern samples. Scanning the pattern via a three-dimensional model, in effect, unwraps it from the curved surface of the tiger's flank and thus also allows a camera trap image of a living tiger to match an image of its skin laid out flat.

Using camera trap images from the Nagarhole and Bandipur tiger reserves in Karnataka, India, we demonstrate the resulting reduction in effort required to generate capture histories from a large database of camera trap images. We also suggest that the software could be used as a forensic tool to trace the origin of tiger skins.

2. MATERIAL AND METHODS

The surface model of the tiger, stored as a text file of three-dimensional coordinates, extends from the shoulders to the base of the tail, undercutting the fore and hind limbs. Figure 1 shows the model fit to a camera trap image and the pattern sample scanned from the flank region. The surface model vertices are the endpoints of rays emanating at intervals from an internal spine, the ray lengths at each interval forming a cosine series function of angle from the dorsal midline, so that initially the model is bilaterally symmetrical. The series coefficients are fixed and were determined by least squares fit to a cloud of surface points generated by photogrammetry, using photographs of a zoo tiger. The computer program initially scales, translates and rotates the model by minimizing the sum of squared distances from shoulder, hip and tail base points on the model to corresponding points on the image, positioned manually on the screen by the user. The model can also twist and bend and thicken or thin differentially along its long axis. A set of four bi-quadratic splines determine the bending and twisting angles and the expansion factors along the model spine. The spline node coordinates introduce a further set of parameters that are then used in conjunction with the scale, translation and rotation parameters to optimize the fit of the projected model to image margins marked by the user.

The same procedure is used to scan left and right flank pattern samples from a photograph of a skin laid flat, except that the surface model used is planar and is not permitted to bend or twist. Thus, as for the live animal photographs, the pattern samples are largely unaffected by camera angle or the scale and orientation of the image.

The pattern sample scanned via the model from the new image is then compared with the database of previous samples. Two algorithms are used to calculate a similarity score between each pair of pattern samples. We omit the details here because a variety of algorithms are available for comparing patterns, but note that, by combining algorithms that are to some extent complementary, it is

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Figure 1. The three-dimensional model fitted to a camera trap image of a tiger. The yellow dots placed on the screen by the user indicate the position of shoulder, hip and tail base points and the red and blue dots indicate the upper and lower margins of the image, respectively (note the second tiger behind the first, which might make automated segmentation of the first image from the background difficult).

possible to reduce the risk of obtaining a low score between matching patterns (i.e. those scanned from images of the same tiger). One of the algorithms is robust to noise in the image but fails when regions of the image are occluded, and the other is robust to occluded regions but sensitive to noise.

The final similarity score is calculated as the posterior probability that the patterns are from images of the same tiger, given the values returned by the two algorithms. The prior probability that two randomly chosen images are of the same tiger could be adjusted to reflect the recorded sex, age and location of the images, but in this case is set simply to the reciprocal of an assumed, local population size, N. If S_c and S_n are the values returned by the two algorithms, the posterior probability that the patterns are from images of the same tiger is given by

$$P(\text{match}|S_c,S_n) = \frac{P(S_c,S_n|\text{match}) \times P(\text{match})}{P(S_c,S_n)}$$

$$= \frac{P(S_c,S_n|\text{match}) \times P(\text{match})}{P(S_c,S_n|\text{match}) \times P(\text{match}) + P(S_c,S_n|\text{non-match}) \times P(\text{non-match})}$$

$$= \frac{1}{1 + P(S_c,S_n|\text{non-match}) \times (N-1)/P(S_c,S_n|\text{match})},$$

where $P(S_c,S_n|\text{non-match}|)$ and $P(S_c,S_n|\text{match})$ are the joint densities of S_c and S_n for non-matching and matching pattern pairs, and are estimated from the frequency distributions of the scores that each member of the pair accumulated as it was compared with the existing catalogue. The value of N affects the posterior probability but not the rank order of the existing individuals. In addition to combining the values into a single similarity score, the posterior probability reduces the expected rank of individuals that tend to achieve higher than average algorithm values (those represented only by low-quality images).

The posterior match probability can be compared with a threshold value, so that only those catalogue individuals from which at least one pattern sample exceeds the threshold are checked visually against the new images. However, in the tiger system, all catalogue animals are ranked in order of decreasing maximum posterior probability, so that the user has the option to search the entire catalogue and any existing match will be found as soon as possible.

3. RESULTS

Camera trap images from the Nagarhole and Bandipur tiger reserves in India were used to test the performance of the system. From 1990 to 2007, in ongoing studies of tiger ecology (Karanth *et al.* 2004, 2006), 227 tigers were identified by patterning on both sides, 37 on the left only and 34 on the right only, thus from 264 to 298 individuals, based purely on careful visual comparison of the images. Pattern samples were scanned via the three-dimensional model from multiple images of each tiger. The similarity score was calculated for every possible pairing of the samples. For each matching pair, that score was ranked against the scores that each member of the pair obtained with non-matching individuals (selecting the highest scoring image of the non-matching individuals). Ninety-five per cent of the matching pairs achieved rank 1 and all were in the top five rank positions. Pairs achieving rank 1 differed in camera angle by up to 66° and by up to 7 years in the date the photographs were taken. The test results are similar to those returned by the system when used with cheetah photographs and are better than those for grey seals. They indicate its ability to locate a match to a new image if the matching individual is currently represented by a single image in the catalogue. The risk of the matching individual failing to achieve a high rank is greatly reduced if multiple images are retained in the database. As yet, the ability of the system to match photographs of cubs has not been tested.

Images of three skins confiscated from poachers were also obtained from 2006 to 2008 (figure 2). Each provided pattern samples from the left and right flanks, which were compared with the catalogue. Five of the six samples generated similarity scores with catalogue images of the living tiger at rank position 1. The sixth sample was taken from the right flank of the skin image in figure 2*c*, in which the skin is partially folded and failed to achieve a high rank position.

4. DISCUSSION

In the current system, the pattern sample is scanned from each new image via a user interface. The time

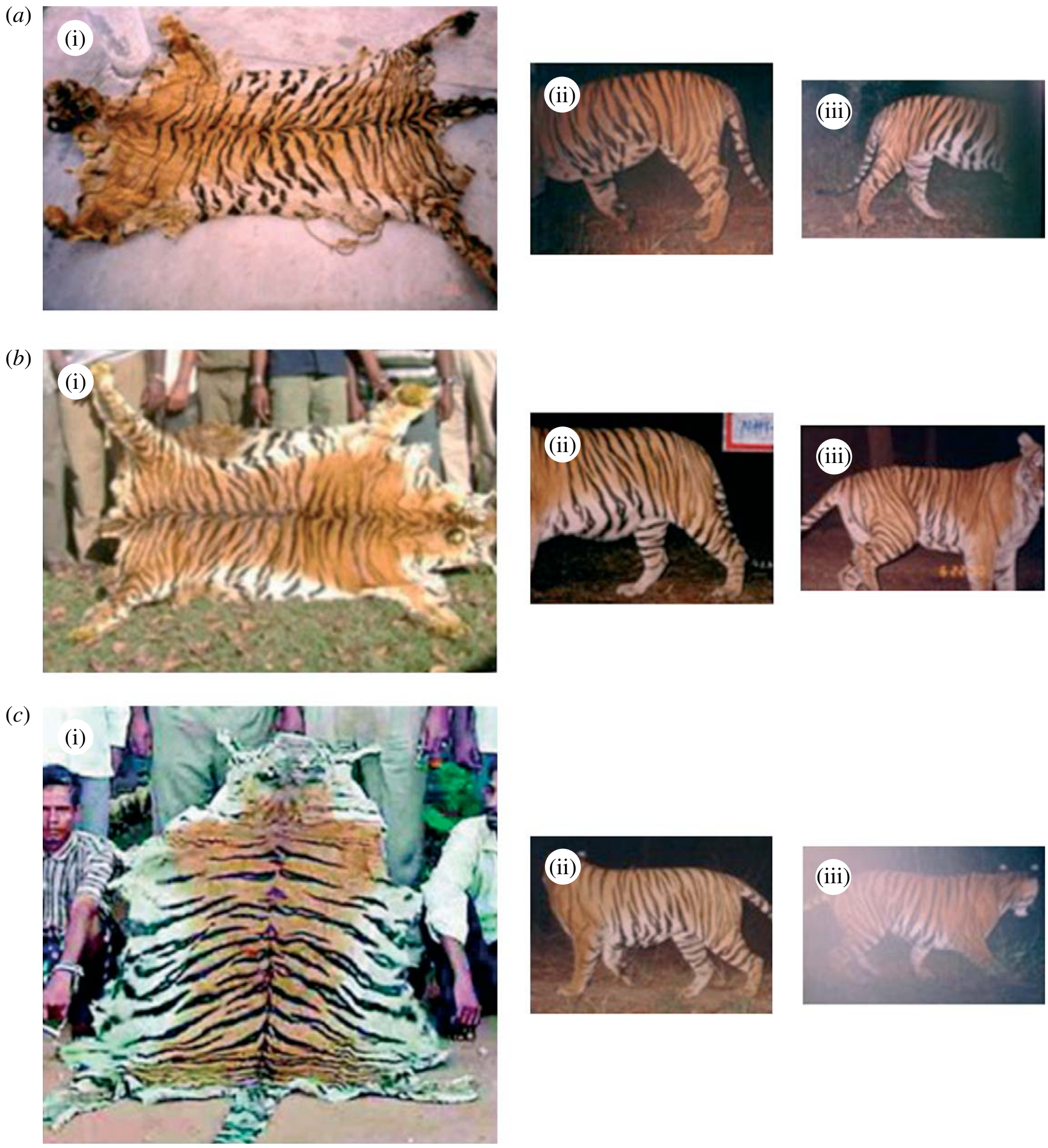

Figure 2. (*a–c*) Images of (i) tiger skins confiscated locally and (ii) left and (iii) right camera trap images of the living tigers taken in the reserves from which the animals were poached. Five of the six pattern samples taken from the skin images generated the highest similarity score with an image of the correct animal from the catalogue. The pattern on the right side of the tiger (*c*(i)) skin image was not scored as similar to the right side of the camera trap image of that tiger (iii).

required to complete that step is not significant in comparison with the effort required to obtain the image and is far less than the 30–45 min currently required for a purely visual search of the photo-id catalogue. However, the user interface introduces an element of subjectivity into the model fitting, and hence a risk of reducing the similarity scores between matching pattern samples if different users are involved. Recent advances in automated detection of animals in video images (Burghardt 2008) suggest that the model fitting step could be further automated.

The algorithms used to compare the pattern samples are also unlikely to be optimal. Nevertheless, the results from the Nagarhole and Bandipur images suggest that the current system is almost certain to place a matching individual from the catalogue at or near the top of the list of similarity scores.

This study also suggests that if copies of camera trap images were accumulated in a central database, an image of a skin that had been taken from one of the tigers represented in that database could be traced within a few minutes to where and when the living animal was last recorded. Such images could be sent from anywhere in the world and would therefore not be restricted to skins located within India. Furthermore, the database need not be restricted to camera trap images and could include, for example, images taken by tourists.

The system has been developed for other uniquely marked species such as leopards, zebras and salamanders. We believe that it provides a tool that is widely applicable for both scientific study and conservation of rare or threatened species.

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