Visual Recapture for Movement Ecology at Interannual Timescales

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Abstract

Capture-mark-recapture (CMR) studies provide essential information on ecological characteristics of rare and endangered species for planning conservation strategies. We develop a system, called Sloop, which recognizes individuals of a species in photographs, using image processing tools organized to benefit from interactive processing, community computing and collaborative science.

Sloop is used to study marbled salamanders (Ambystoma Opacum) in a nearly 10 year capture history. The indexing process has been completed up to 2004. Ongoing effort to expand indexing to 2008 and extend Sloop to other species is underway. Sloop saves indexing time by two orders of magnitude over manual searching and new scientific results continue to emerge from the visual capture histories.

1. Introduction

The development of effective conservation strategies for rare, threatened, and endangered species requires unbiased and precise information on their life history. For example, a recovery plan for a declining amphibian species may require spatio-temporal estimates of survival, fecundity, and dispersal. CMR studies enable researchers to identify specific groups (i.e. 'cohorts') or individual animals. Though some questions can be investigated using cohort marks (e.g. 'what percentage emigrates beyond a particular distance?'), many others depend on the ability to identify individual animals. These include questions related to individual growth and survival (including age- or size-dependencies), dispersal and movement, and reproductive strategies.

CMR studies typically use techniques in which animals are physically marked or tagged (e.g. with ear tags, PIT tags, leg bands, shell notches or dyes [14, 20]. These methods are intrusive to varying degrees and in some cases may affect the fate and/or behavior of the animals being studied [15, 12]. In addition, some taxonomic groups like amphibians may be difficult to tag efficiently in large numbers (e.g. due to small body size or constraints of field conditions) or may not retain marks or tags long enough to be useful. Alternative identification techniques that overcome some of these limitations are needed.

Numerous efforts have been made to identify individual animals using photo-identification methods [9, 5, 2, 11]. Individuals are photographed and later identified through visual matching, sometimes aided by one of the following strategies to narrow the scope of manual searches: (1) coding of distinctive features (e.g. fluke patterns and scars in whales) into a searchable database; (2) manual or semi-automated extraction of morphometric information (e.g. dorsal fin ratio); or (3) analysis with pattern recognition algorithms. The first approach made searches feasible in catalogs with thousands of whale images; however, in performance tests only 57% of known matches were identified in the top 5% of database-ranked images [13]. The second approach has been applied to dolphins and fish [1], but is limited to cases where clear and variable morphometric information is available. Published accounts of the third approach using pattern algorithms have been mostly limited to large-bodied animals (e.g. whales, cheetahs) and small test data sets.

We develop a system called Sloop that provides a set of image processing and pattern recognition tools for indexing individuals of a species using their photographs. Sloop uses multiscale features and a matcher incorporating user relevance feedback to produce a capture history of an individual. We believe that this approach offers many new opportunities in conservation-related research by: (1) improving recognition performance substantially, and thus increasing the spatial and temporal scales at which capture-recapture investigations can be conducted; and (2) extending the reach of pattern recognition algorithms to a greater variety of patterned organisms, in particular because it does not rely on discrete geometric pattern features such as spots or stripes.

We describe an application of this method to the marbled salamanders, which are primarily terrestrial salamanders, characterized by a black and white 'marbling' pattern (see Figure 1) that appears to be individually unique and stable over time. Marbled salamanders occur in upland and floodplain forests across much of the eastern United States, and migrate to seasonal pond basins in the late summer and early autumn, where they court and deposit eggs in terrestrial nests. The eggs hatch into aquatic larvae shortly after inundation by rising pond waters, and metamorphosis and emergence occur in the following summer. Though seasonal ponds provide essential breeding habitats for many amphibians and invertebrates, they receive limited regulatory protection and are considered to be a declining habitat resource. As a result, there is concern that many pond-breeding amphibians, including marbled salamanders, may be declining due to habitat loss and fragmentation [18].

2 Pre-processing and Matching

Images of salamanders come in two types, legacy images acquired in natural conditions (see Figure 1) and modern ones acquired using a custom-designed apparatus with an artificial background (see Figure 3). Both these images are acquired from traps placed at intervals along a fence around several (14) ponds.

Once an image is uploaded to the database, it undergoes a pre-processing stage before recognition and indexing. Pre-processing involves illumination correction, segmentation, and rectification to a canonical geometry. Size and contrast normalized patches are extracted from the resulting image in a coordinate system determined by *fiducials* associated with an individual. Once an image is normalized in this way, we compute multiscale differential features [16] and match the resulting multiscale feature template with others in both the space of amplitudes and positions [17]. These steps are discussed further.

After initial pre-processing, an axis of symmetry (the medial axis) is detected on the individual and its remapping (medial axis curve to the straight line) deforms the salamander into a rectified pose. Points where feet emerge from the body are used as fiducials to determine

Figure 1. An imaged marble salamander that has been straightened and segmented.

a body window. The body window is stochastically perturbed in position and scale several times and image patches are extracted for each perturbation, and normalized to fixed dimensions. Each patch sample of a single imaged animal is filtered at multiple scales to produce differential features of first and second order [16]. They are *stacked* into layers of 2D templates.

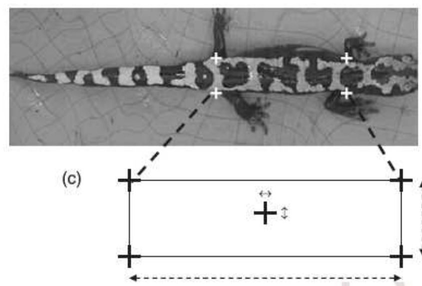

Figure 2. Body window associated with fiducials.

To match two feature templates, we use the following objective [17]:

$$J(q) := ||X(p-q) - Y(p)||_C + w\ Lq \qquad (1)$$

Here, X is a multiscale feature template matched with another multiscale feature template in the space of *amplitudes* using a norm with covariance C *and* in the space of positions defined by the vector q, which represents a displacement at every pixel of the multiscale feature template. The matrix C is estimated from the population of salamander images. The matrix L represents regularizing constraints, chosen here so that q occupies very low wave-numbers, i.e. is smooth (but this does not imply it is piecewise affine, such a transformation can contain very high frequency deformations). This equation is minimized for q using conjugate gradients, at the end of which we have a total cost that accounts for the work done displacing and the difference in feature values.

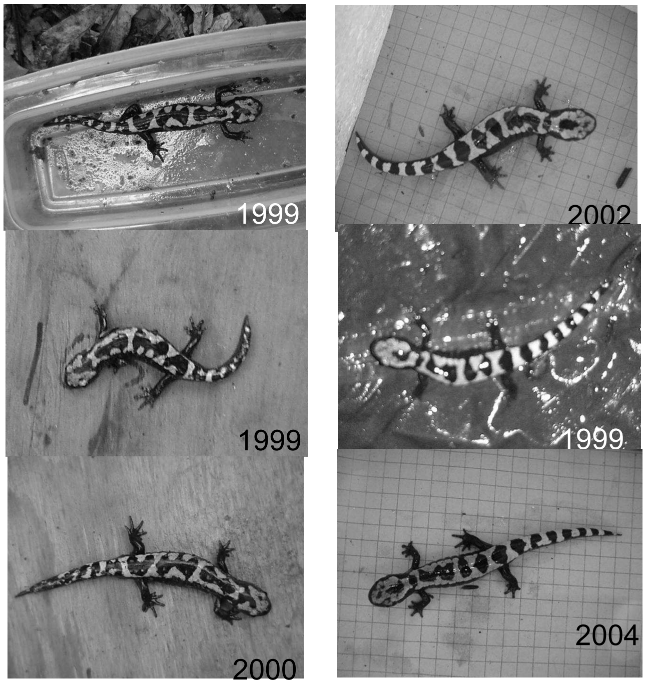

Figure 3. Examples of queries and their matches, read vertically. The year of capture is annotated.

Every image in the database is matched with all the other images in this way and ranked. To test the performance of the pattern algorithm, we manually identified 100 queries with known matches and then embedded this test set into a large collection. Results indicate that a 95% accuracy can be attained within the top 10 ranks.

But because mismatches do occur, we have developed a relevance feedback step. The user verifies the matches by looking at the top ten ranks and identifying the matches. When more than three matches exist, C is modified to reflect the covariance of this subpopulation. In this way, preliminary results indicate that we can lift the performance to about 98% recognition rate in a few iterations.

Images that have been identified as matches are reported as a capture history and used for biological analysis.

3 Biological Application

The capture histories have allowed us to evaluate aspects of movement, timing and weight change in the breeding cycle of marbled salamanders and reported elsewhere [6, 7, 8]. Briefly, of the animals captured and identified on more than one occasion, the majority (94%) were captured twice at the same pond basin, suggesting that migratory movements were strongly oriented to and from breeding sites in this species and that multiple entries and departures from basins were rare. This is in contrast to Trenham's finding that breeding California tiger salamanders Ambystoma californiense often entered and departed basins multiple times within the same season [19]. However, around 15% of breeding individuals in this season were first-time (i.e. inexperienced) breeders. By searching over 7000 images in the period 1998-2004, we are able to conclude that this small fraction of a pond's population is key to long-term population stability [6, 7]. From a conservation point of view this strongly supports the idea that it is not merely sufficient to fence off a pond in an effort to conserve the population within. The length-scales necessary for viability is much larger (order kilometer), which is surprising considering the size of the individual and its net mobility per day. These results were not known or believed prior to this finding.

4 Conclusions

Our results suggest that a semi-automated process using pattern algorithms can provide an effective alternative to more intrusive techniques for identifying individual animals. With a 95% recognition rate and less than 30 s per image the time it required to process is orders of magnitude faster than manual approaches.

We contend that our approach does not depend on discrete geometric features such as spots or bifurcations in striped patterns, and therefore can probably be extended to a broad variety of organisms and patterns (e.g. leopard frogs, wild dogs, numerous moths and butterflies). Indeed preliminary work on the tiger salamander (spotted patterns) and Fowler's toad (fine texture) indicate that this is a reasonable statement.

There are, of course, limitations to a visual recognition-based approach; most notably, the dependence on some permanent and 'extractable' pattern information. Marbled salamanders, for example, lack distinctive patternation as juveniles and thus require different identification methods in pre-adult stages. But in numerous cases, the investment in an algorithmic approach becomes essential in cases where sample sizes are large, making manual approaches labour-prohibitive. These cases are probably most common with smaller-bodied animals.

There are also analytical limitations presented in the interpretation of these data with regard to errors. Errors of omission (i.e. 'missed matches') can occur if a matching image is not ranked highly enough to be verified, or if the image is highly ranked but is not recognized by the observer. A different type of error can occur when an observer incorrectly links two images of different individuals.

There are several priority topics that, with additional research and development, can extend the usefulness of this approach to other ecological applications. Pairing the multi-scale algorithm with 3-D models for pattern extraction [10] may also improve performance in some cases, extending its applicability to organisms and study designs where standardized image acquisition is not possible. Lastly, though the disciplines of computer vision and wildlife ecology have historically been disconnected, recent projects indicate potential for new collaborations.

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