Virtual 3D Models of Insects for Accelerated Quarantine Control

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Abstract

We learn from the past that invasive species have caused tremendous damage to native species and serious disruption to agricultural industries. It is crucial for us to prevent this in the future. The first step of this process is to identify correctly an invasive species from native ones. Current identification methods, relying on mainly 2D images, can result in low accuracy and be time consuming. Such methods provide little help to a quarantine officer who has time constraints to response when on duty. To deal with this problem, we propose new solutions using 3D virtual models of insects. We explain how working with insects in the 3D domain can be much better than the 2D domain. We also describe how to create true-color 3D models of insects using an image-based 3D reconstruction method. This method is ideal for quarantine control and inspection tasks that involve the verification of a physical specimen against known invasive species. Finally we show that these insect models provide valuable material for other applications such as research, education, arts and entertainment.

1. Introduction

Australia has many unique ecosystems with a wide range of native terrestrial and marine animals and plants. Australia also has multibillion-dollar agricultural industries. Therefore it is crucial for the country to protect its ecosystems and agricultural industries from invasive species. This is a challenging task due to the fact that, like other modern societies, Australia is relying heavily on trading with foreign countries. As a result, a huge amount of cargo is transported into Australia everyday by air, sea and land, providing a pathway for exotic diseases and pests to enter the country. Containers and vessels can bring in invasive pests both in their contents and attached to their structures. Furthermore, luggage carried by passengers from overseas can also contain infested plant and animal products. Therefore it is crucial that we discover invasive pests before they enter the country and cause serious damage to our industries and environments.

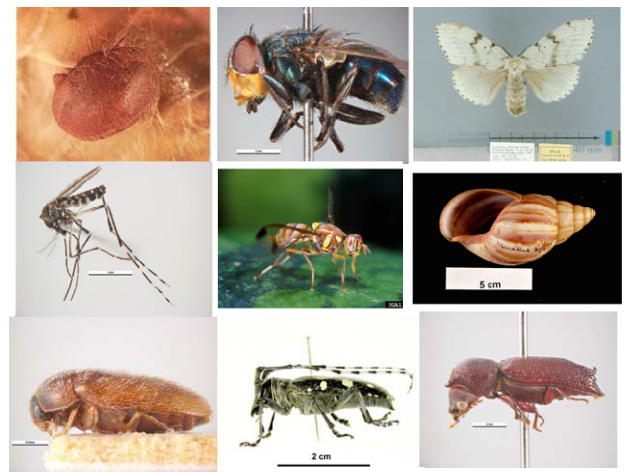

Figure 1. Some of Australia's pests of animals and plants. From left to right, top to bottom: Varroa mite, screw-worm fly, Asian Gypsy moth, Asian tiger mosquito, fruit fly, giant African snail, Khapra beetle, longhorn beetle, Lesser Auger beetle. Source [1].

Figure 1 shows several exotic animal and plant pests as identified by the Australian Department of Agriculture and included in "Australia's most unwanted" book [2]. The larvae of screw-worm flies can kill their host animal if left untreated. The Khapra beetle is one of the world's most serious plant pests. Its larvae feed on grains and other stored products and are very difficult to eradicate.

There are other image resources of insect pests, such as the Pest and Disease Image Library [1] and the Atlas of Living Australia [3]. These resources play a major supporting role in protecting native fauna and flora from invasive pests and diseases.

By careful inspection of cargos, containers and vehicles, quarantine control can intercept new insects at the ports. However, correctly identifying pest insects is still a difficult and time-consuming task that often requires support from expert entomologists.

1.1. Insect identification using 2D images

To prevent an invasive species from entering the country, the first step is to correctly identify and distinguish it from native species. This is still a major challenge, for several reasons.

One is that native species living in a similar habitat as a potentially invasive one are often also very similar morphologically and difficult to distinguish using even detailed 2D images. Figure 2 illustrates this by contrasting dorsal views of the notorious Rice Water Weevil (*Lissorhoptrus oryzophilus*), which is a serious pest of rice in many countries and has a high potential of being introduced into Australia, and of a harmless native species, *Bagous australasiae*, which also lives in aquatic environments but does not attack rice.

Figure 2. 2D images of the dorsal view of two similar aquatic weevils, left the potentially invasive rice pest *Lissorhoptrus oryzophilus* and right a native Australian species, *Bagous australasiae*.

Apart from the problem of the large number of existing insect species, the appearance of a single species can vary significantly from one viewing angle to another. Figure 3 illustrates such problem; the same butterfly shows different patterns on its wings and body from different viewing angles. Animals can additionally adopt different postures, an especially crucial aspect in winged insects, which further makes it difficult to correctly identify a species.

Figure 3. The same *Danaus petilia* butterfly photographed at different angles shows different patterns. Such strong view-dependence can make a species difficult to identify. Source [3].

Another problem is that, as insect body structure can be highly complex, an image or two is often not sufficient to provide sufficient information about its critical features. As shown in Figure 4, the top and bottom views of a bug do not provide enough information about its legs, which is only available in a side view. Even then, however, due to occlusions these three images still do not provide sufficient structural information about the bug.

Figure 4. A bug (*Melanocoryphus albomaculatus*) photographed in three orthogonal views. Only the side-view image provides relevant information about the leg structure. Source [4].

Although large image repositories of insect pests such as [1] and [3] are available on the Internet, they still provide only raw information, searchable only through text input, and are therefore mostly usable to entomological experts. For non-expert users, Internet services such as Google provide an image search facility as a way to find similar image content of any object. When a user drags and drops an image of an object onto the search window, Google returns similar images and related information. However, as the Google image search engine is not optimised for insect images, the results are very unreliable without additional information.

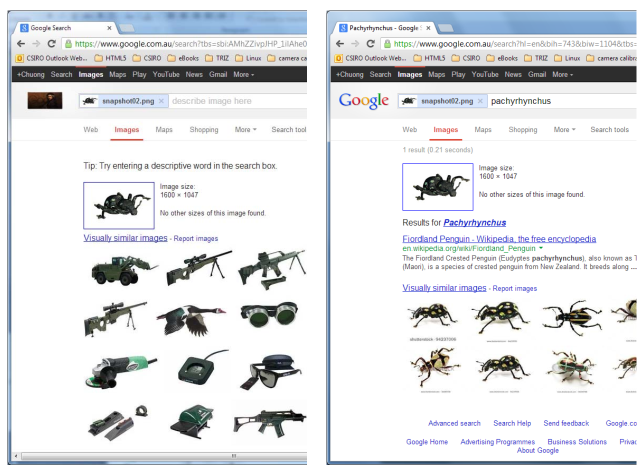

Figure 5. Google image search [5] can provide unexpected results from an input image of a specimen (left). With more detailed information (right), Google can return better results.

Figure 5 shows that a Google search of a weevil image returns completely unrelated images, such as weapons and tools. Only by adding the scientific name of the weevil can Google return related images and additional links.

There are methods for an untrained person to identify insects at order level, i.e. insect families, from 2D images or physical specimens. A person can follow a check-list (such as [6], [7]) step-by-step until arriving at the correct family. Furthermore, software solutions have been developed for automatic identification of insects at order level. Wang *et al*. [8], [9] proposed such a method, with the accuracy varying significantly from poor to excellent, depending on the similarity between orders and the captured insect postures.

The current identification process at Australian ports is often for a professional entomologist working remotely and offline to provide accurate identification of a specimen [10]. However, in many circumstances, a quarantine officer has to make a decision within a short time and an expert entomologist is not immediately available.

1.2. Insect identification using 3D models

In this paper we propose to move from 2D images to 3D models to better deal with the insect identification challenges. Such a shift has two major potential benefits.

First, the human mind perceives objects in 3D and can quickly recognize a familiar figure from a distance. This equally applies to insect identification. A collection of 3D digital images of known invasive pests at hand to match with physical specimens can make quarantine inspection much easier and more reliable. Our demonstrations of 3D models of insects have elicited great interest in using such models in training quarantine officers to identify invasive pests more accurately and quickly.

As a practical example, Figure 6 shows the difference between the rostral canal and receptacle in the Mango Seed Weevil (*Sternochetus mangiferae*) and a similar native Australian weevil, *Camptorhinus inornatus*. The shape and origin of the receptacle (on the mesosternum in the former, on the prosternum in the latter) is only discernible in a particular oblique view, requiring careful and comparable rotation of the specimens in several directions. Ordinary lateral and ventral 2D images cannot achieve this, but a fully rotatable 3D model can easily do so and enable a quarantine officer to quickly check this particular important feature.

Figure 6. Differences in the shape and origin of the rostral receptacle in the Mango Seed Weevil (*Sternochetus mangiferae*) and a similar Australian native species (*Camptorhinus inornatus*), These differences are only visible in a particular angle of view, readily achievable with 3D models but with great difficulty using traditional 2D images.

Second, recent advancements in 3D shape matching make it possible to automate or semi-automate the insect identification process. Shilane *et al*. [11] provided a review of shape-matching algorithms and benchmarked them against a large 3D database including models of insects such as ants, bees and butterflies. Ohbuchi and Furuya [12] proposed a 3D-model retrieval method that successfully matches partial 3D insect models with full models in a database. Additional pattern matching can improve the success rate and potentially lead to higher levels of identification of species.

The main obstacle is the timely acquisition of 3D models of insects, and this paper aims to solve this problem.

1.3. Existing works on image-based 3D modeling of insects

Image-based 3D reconstruction techniques have undergone significant advances in achieving realistic 3D models. Excellent reviews of major advances can be found in [12] and [13]. Notable recent works include [15]–[17]. These have been successful in reconstructing large-scale 3D models of cities and objects usually of simple shapes.

In contrast, there have been few attempts to apply image-based 3D reconstruction to small biological specimens. Atsushi *et al*. [18] described a micro-object scanning system, demonstrated with 3D reconstruction of a ladybird beetle. Gallo *et al*. [19] described a simple multi-view scanning system for small marine organisms of strong texture, ideal for reliable 3D reconstruction. Chalmers *et al*. [20] presented a structured-light technique with lens shifting to achieve sub-pixel resolution and enhanced depth accuracy for small flat objects such as leaves and coins. These methods, however, do not specifically cater for insects with complicated structures and strong peculiar reflections.

There have been attempts to utilise human inputs and 3D-to-2D fitting to tackle the challenges of constructing realistic insect models. Zhang *et al*. [21] proposed a method to infer a 3D insect shape from a single 2D image. However, this method is limited to simple insect geometries. Murakawa *et al*. [22] proposed to fit a template of similar 3D insect models to orthogonal views of an insect specimen. This method additionally requires manual inputs to guide image registration and geometric transformation.

The method described in this paper generates very high-resolution 3D color models of insects, each from hundreds or thousands of images. It applies well to insects with complicated geometries and even strong peculiar reflections. It is currently in a proof-of-concept stage and under rapid development. The following sections describe our 3D reconstruction prototype and initial results.

2. Method and materials for 3D modeling of insects

2.1. Image acquisition

For image acquisition, we have assembled a customized system from off-the-shelf components. The system captures high-resolution multiple-view images of specimens with sizes from a few millimeters to a few centimeters. The system as shown in Figure 7 consists of:

- A 2-axis turntable: a GigaPan EPIC 100 panorama robot modified to function as a 2-axis turntable.
- A camera: a Canon EOS camera (600D or 5D Mark II) with resolution of 18MP or more.
- A macro lens: a Canon EF 100mm macro lens for insects of 10 mm and larger, or a Canon MP-65mm 1-5X macro lens for insects smaller than 10 mm.
- A flash light: a Viltrox JY-670 ring flash and a Tronix SpeedFire external power supply for fast charging.
- A macro rail to capture multi-focus images: a Cognisys StackShot macro rail. The control box for the rail is modified to accept a trigger signal from the turntable to start scanning and to capture images at different depths.

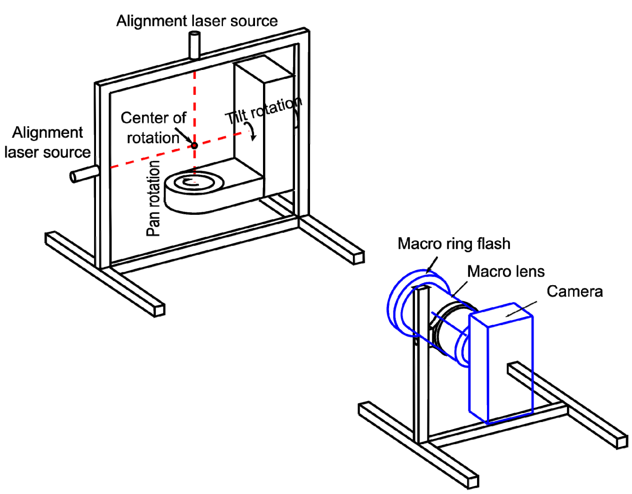

Figure 7. Image acquisition system with a 2-axis turntable and a macro-lens camera. For multi-focus image acquisition, the camera is attached to a macro rail that translates the camera along its optical axis.

Capturing images of insects larger than 10 mm is relatively simple. A specimen is attached onto the 2-axis turntable at the center of rotation, and rotated step-by-step around the vertical axis and horizontal axis. At each rotation angle, the turntable triggers the camera and the flash to capture an image. The camera lens is adjusted so that the whole insect is in focus. The more images captured at different angles, the better the 3D models to be generated.

2.2. Depth-extended image acquisition

With insects smaller than 10 mm, the camera has to captures images at higher magnification to reveal the details of the specimen. At high magnifications, the depth of focus of the camera lens can be smaller that the size of the object. As a result, only part of the specimen is in focus at a time. Resulting partial-focus images lead to low-resolution and low-accuracy 3D models.

A simple solution to increase the depth of focus would be to reduce the camera aperture. However, due to lens diffraction effect, smaller camera aperture leads to lower optical resolution. This effectively leads to 3D models of low resolution and low accuracy. This effect has been reported by [19] and was confirmed by our experiments. As a result, the camera aperture has to be large enough to maintain acceptable optical resolution.

To obtain an image with the entire specimen in focus and without sacrificing optical resolution, multiple images are captured at different focal depths along the camera optical axis. These images are then numerically stacked together to form a single image containing only in-focus parts of the specimen. There are open-source and commercial software programs that can be used to perform this image stacking, such as CombineZP [23] and that of Hugin and Enfuse [24]. We found that a commercial software called Helicon Focus® [25] provided better processing speed and ease of use with large image sets.

Another problem relating to high-magnification lenses is motion blur. Most professional digital cameras still use a mechanical shutter to control exposure time when capturing an image. Normally, vibration from the shutter has negligible effect to image quality. However, when an image is captured at high magnification, a small vibration movement is also magnified, leading to significant motion blur. Flash light is therefore used to reduce effective exposure time to a few milliseconds and thus eliminate motion blur.

2.3. Specimen alignment

For maximum 3D model quality, it is crucial that, during scanning, a specimen stays within the depth of focus, or within the depth range of multi-focus images. To prevent the insect from moving too much while rotating, the specimen needs to be located at the center of the rotation, i.e. the crossing point of the two rotation axes of the turntable. To achieve this goal, we set up a pair of laser pointers, each pointing along the rotation axis. The specimen is aligned manually to each of the laser beams, such that each beam hits the center of the insect's body.

2.4. Specimen mounting orientation

Traditionally, insects are kept in collections in a horizontal position, with a pin passing through the body from the top. This way of mounting makes it difficult to capture images of the underside of the specimen. To avoid this constraint, specimens to be scanned are mounted vertically, with the body aligned to the vertical rotation axis of the turntable. Depending on scanning constraints and desired characteristics of the final 3D model, the original pin can be removed prior to remounting the specimen for 3D imaging.

2.5. 3D reconstruction

Images captured around a specimen are processed to create a 3D model. We currently use a commercial software package called 3DSOM [26] for 3D reconstruction from acquired images. The details of the algorithms used in this software are described in [27]. This software is based on visual-hull reconstruction method, with optional 3D point-cloud computation for improving the visual-hull model. In practice, we found that the quality of the 3D point cloud for insect specimens is too poor to make any improvement to the visual-hull 3D models.

The 3DSOM software requires a special *mat* pattern to be attached to a specimen so that the software can estimate camera poses relative to the *mat* pattern and the specimen for 3D reconstruction. During 3D reconstruction, camera poses are further refined to improve the accuracy of the resulting 3D model. In addition, if the camera captures images with significant optical distortion, an additional step of camera calibration is required to estimate lens distortion and numerically correct for it.

The visual-hull-based reconstruction method requires input images to be segmented to separate the specimen from the background. This image segmentation step can be performed using a separate software or within the 3DSOM environment. The accuracy in image segmentation also determines the quality of the final 3D model.

3. Results

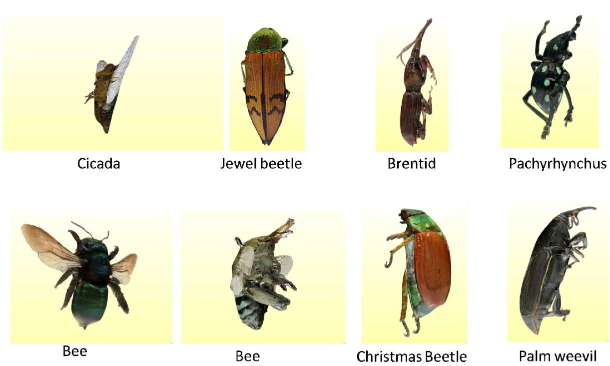

Figure 8. Snapshots of 3D models of various types of insects

Figure 8 shows snapshots of 3D models of various insects with different wing configurations, colors and reflective surfaces. They are all larger than 10 mm and can be photographed with a macro lens of magnification of 1 or smaller.

Figure 9 shows insects of different sizes, ranging from approximately 3 mm to 30 mm, and their corresponding 3D models rendered with and without texture information to show the reconstruction quality.

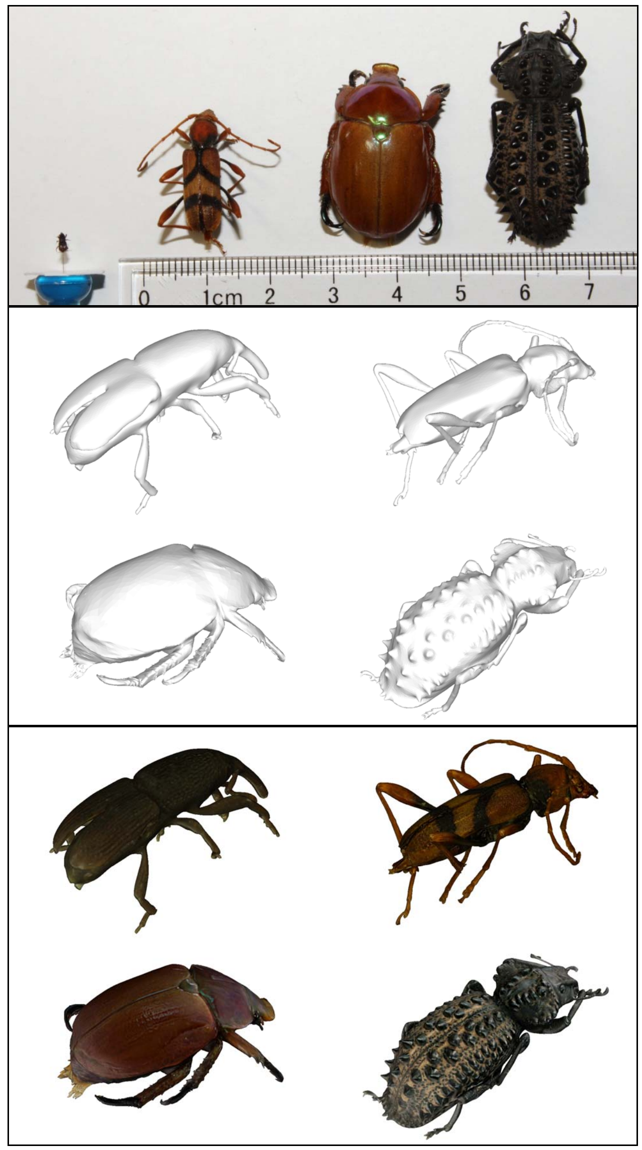

Figure 9. 3D models of insects from 3 to 30 mm long. The top box shows photographs of the actual insect specimens, f.l.t.r. a grain weevil, a longhorn beetle, a Christmas beetle and an amycterine ground weevil. The middle box shows the 3D shapes of the reconstructed models (not to scale). The bottom box shows the same models, with full color textures.

For demonstration, a 3D model of the longhorn beetle shown in Figure 9 is made available at [28]. The model can be viewed and manipulated using open-source software such as MeshLab [29], which is freely available for PC computers, iOS and Android devices.

4. Additional applications

There have been significant needs to accelerate our knowledge of biodiversity and the role that improved image analysis capabilities and the digital imaging of museum specimens can play in this effort, as described in [30]–[38]. 3D insect modeling can become a centerpiece of such development, improving digital access to our collections and enhancing the recognition of our biodiversity.

Most of insect models in this paper have also found a home in several *science art* works, in major public events and as part of the Canberra of Centenary 2013 celebrations. These works include *StellrScope* [39], Enlighten Canberra [40] and Embracing Innovation Volume 3 [41]. The outcome, through public events, provided major public engagement with scientific research and directing increased interest into research at CSIRO.

5. Conclusion

We suggest that current imaging methods using 2D images are insufficient to support quarantine control within realistic time constraints and that 3D models of potential invasive species will open new solutions to the problem of their rapid and accurate identification. We present a new method to create accurate 3D models of insects and show the initial results obtained from our system, which produces high-resolution 3D color models of insects with a wide range of body size and complexity. The insect models generated have also proved useful for research, education and entertainment.

The future direction of this research will seek to develop a 3D-search algorithm specialized for insects to validate the effectiveness of 3D insect models in distinguishing invasive pests from native species.

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