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Single viewpoint model completion of symmetric objects for digital inspection

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ABSTRACT

The ability to create complete 3D models of real-world objects is an important task for various applications. In digital inspection, complete models allow users to analyze the entirety of an object. However, various difficulties arise for image-based acquisition techniques. First, the viewpoint planning problem must be solved. Second, each of the resulting view point captures must be combined with either zippering or 3D triangulation, both difficult problems. We observe that if an object is symmetric, then the object's symmetry can be exploited so that a single viewpoint capture is sufficient to generate a complete, 3D triangulated model. In our work, three problems of previous approaches to generating complete models are avoided or minimized: (1) we avoid 3D triangulation, (2) we avoid searches for geometry to extend our models, and (3) we minimize viewpoint planning to the selection of a single viewpoint. Our approach also includes algorithms to mitigate global deformations due to capture error. We demonstrate our approach by capturing, reconstructing, and completing several scenes of one or more objects and illustrating several digital inspection methods with these scenes.

1. Introduction

We present a method to obtain complete 3D models of real-world symmetric objects for use in digital inspection. Digital inspection provides tools for non-experts to closely examine the details of a captured object. For example, an artist, archaeologist, or historian might wish to digitally magnify surface details, to relight the objects, or to create synthetic illustrations. In these situations, complete 3D models enable the user to digitally inspect more than that which is initially captured – this can be particularly useful when dealing with an artifact fragment where the remainder of the artifact is lost. Being able to quickly and virtually slice a virtually completed object provides a powerful visualization ability. Moreover, a low-cost and easy-to-use approach permits its easy and widespread dissemination.

Thus, a major challenge of digital inspection is to obtain complete, high-resolution models for a comprehensive inspection of the object. While approaches to acquiring complete models have been proposed, each approach has its own challenges. Manual modeling using computer software is a time consuming option. 3D acquisition methods (e.g., structured-light [22], laser scanning [10], or passive stereo [17]) can capture models, but obtaining complete models requires special equipment or multiple viewpoints to observe the entire object. The multiple viewpoint requirement introduces viewpoint planning [23]. Additionally, the acquisitions from multiple viewpoints must be aligned (e.g., with Iterative-Closest-Points (ICP) [3,21]) and zippered [29]. In both steps, the negative effect of deformations in the acquired fragments must also be addressed. The acquired fragments' points can alternatively be merged via 3D triangulation, a complex problem in itself (e.g., handling noise and avoiding holes or other artifacts [5]). For scenes with multiple objects, acquiring complete models is even more difficult due to potential visibility constraints being introduced. In fact, if the objects are of high importance and manipulating or re-arranging them is not an option, there may not be a practical configuration that enables capturing all of the objects' surfaces. Altogether, the task of a digital inspection system is confronted with several model acquisition issues and limitations in viewpoint planning, 3D triangulation, and the registration of multiple scans to form a single model.

Our key inspiration is to exploit the symmetry present in objects to extrapolate a plausible complete model of an object from a single viewpoint. In doing so, we minimize or avoid three problems of previous works: (1) the viewpoint planning problem is reduced to choosing a single viewpoint where the object's symmetry is identifiable; (2) 3D triangulation is avoided, and the initial single viewpoint capture is triangulated in 2D image space; and (3) since symmetry can be used to identify geometry for filling in holes and for extending the model beyond its captured borders, searches to find suitable geometry (as in [14,25]) to complete the model are unnecessary. The same principles apply with no additional difficulties for scenes with multiple objects, thus enabling the acquisition and inspection of multi-object scenes with minimal additional effort. Nevertheless, there is no explicit guarantee that the

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extrapolated models are exact matches of the original objects. For example, if a unique feature of the object was not in the initial capture (e.g., a vase's handle), then the requisite geometry to replicate the feature would be missing in the final model. For an approximately symmetric object (e.g., a manmade object intended to be symmetric but is not due to human error), the slight asymmetry would not be captured. Despite these limitations, our method is still suitable for a wide range of objects.

Our approach to 3D model completion for digital inspection consists of four steps (Fig. 1). First, from a single viewpoint, we capture a detailed fragment of an object. Second, we manually select the object's symmetry class – we support three common symmetry classes: bilateral symmetry, rotational symmetry, and surface-of-revolution symmetry – and automatically discover the relevant symmetric features. Third, symmetric geometry fragments are replicated and merged with our custom zippering process to construct a complete model. Then, under user control, we assume the object to be either solid or hollow and either close the mesh or add an inset to create a plausible interior surface for the model. Finally, we interactively generate digital inspection illustrations of the completed models using techniques similar to [1,19]. Our approach is fully automated aside from choosing an object's symmetry class and the closing style of the resulting model. We have applied our method to capture individual models ranging up to 900k triangles and multi-object scenes ranging up to 4.1 million triangles, and the resulting models have an average sampling resolution of 0.35 mm.

Our contributions are twofold. First, we present robust symmetry algorithms for our three types of supported symmetry capable of identifying the global symmetry of a model from a fragment of it. Second, we describe a method for producing complete models of the objects from a single viewpoint, including a zippering procedure capable of adapting to irregularities between fragments. We also describe techniques to better improve the quality of symmetry detection as well as mesh zippering where appropriate.

2. Related work

Our work spans research in acquisition and modeling, symmetry detection, and visualization and rendering. We summarize the relevant research below.

2.1. Acquisition and modeling

Various techniques exist to acquire high-resolution 3D models using image sequences, lasers, or structured-light (e.g., [2,10,17,22]). The motion of an object can also be tracked (e.g., across video frames [11] or by hand [20]) to generate a model, where tracked captures represent view points observing the object [11]. These approaches obtain complete models by increasing the number of capture viewpoints. However, the viewpoint planning problem to decide where to acquire additional data remains a difficult and open problem.

Several techniques have been proposed to complete or expand 3D models from fragments. A priori databases of shapes can provide geometric priors for filling in the holes of a model or for synthesizing new models (e.g., [7,14,24]). Searching for a suitable patch in the model itself has also been proposed (e.g., [25]). Symmetry removes the need to search for suitable geometry.

Combining separately acquired mesh fragments traditionally requires an alignment process (e.g., ICP [4,8,21] or 4PCS [6]) and zippering [29]. Warping functions (e.g., [14]) and Poisson-based gradient field manipulation (e.g., [30]) have also been proposed in order to alter mesh fragments to fit seamlessly. Symmetrization [13] enforces symmetry in meshes, but the result may incorrectly warp the geometry. Enforcing symmetry during acquisition has also been explored (e.g., for bilateral symmetry [31]). While this would help alleviate capture errors, we opt to alter the mesh's geometry after acquisition. Combining symmetric fragments is unique in that the fragments are already reasonably aligned and shaped. Thus, our zippering process avoids an alignment process, and only a small amount of mesh warping and interpolation is needed.

2.2. Symmetry detection

Our method requires detecting the global symmetry of an object from a fragment of it. Methods identifying symmetry only in the capture geometry (e.g., [12,16,26]) are inadequate since they do not consider the symmetry beyond the capture borders. Voting based techniques (e.g., [12,16]) may detect an object's global symmetry, but depending on the amount of global symmetry evident in the capture, local symmetries may be more strongly identified. With our capture fragments, we avoid incorrect classifications from ambiguous configurations (e.g., two captured faces of a rotationally symmetric object may exhibit bilateral symmetry; a surface-of-revolution fragment inevitably exhibits rotational and bilateral symmetry) by letting the user select the symmetry class with a simple interactive selection. Instead, we focus on obtaining plausible, complete models.

A variety of shape-fitting and shape-classification methods have been proposed to detect symmetry from fragments (e.g., fitting

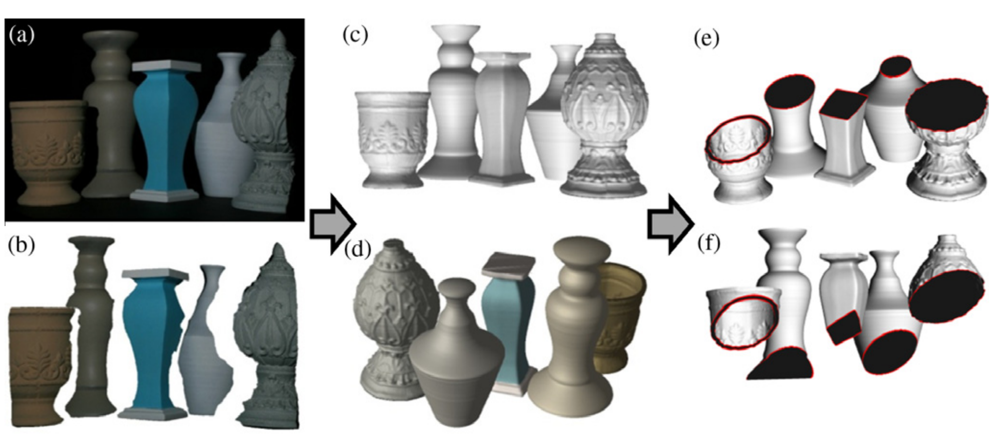

Fig. 1. Single viewpoint model completion for digital inspection. (a) Picture of a multi-object scene. Left to right, these objects are 'Small Vase', 'Tall Pedestal', 'Pedestal', Smooth Vase', and 'Saint'. (b) Initial single viewpoint reconstruction. (c) Completed models of the observed objects rendered in grayscale from a vantage point different from the capture viewpoint. (d) The completed models texture-mapped. (e–f) Interactive digital inspection examples using the objects produced by our method.