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A Strategy for Establishing 3D CAD Model Dataset of Reactor Vessel Components

Sungmoon Joo*, Ikjune Kim, Dongjun Hyun, and Jonghwan Lee
Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, Korea
**Corresponding author: smjoo@kaeri.re.kr*

1. Introduction

Control applications such as reactor operation or remote handling in decommissioning of nuclear facilities involve trajectory generation. For example, we want the reactor power to follow smooth trajectories without abrupt changes in control reactivity or we want to move remote handling manipulators smoothly for safe handling of hazardous radioactive materials. These trajectory generation problems can be modeled as a point-to-point motion problem in control theory.

Robotic nuclear decommissioning scenarios [1] rely on recognizing 3D properties of reactor vessel components. This puts 3D object recognition as one of the central problems in robotic nuclear decommissioning system.

Remarkable progress has been achieved in 3d object recognition after the introduction of several 3D model databases. However, these datasets are limited in scale and include only about a dozen ordinary object categories, while robotic nuclear decommissioning scenario requires the recognition of industrial, more specifically nuclear industry, objects.

In this study, we review couple of datasets for 3D object recognition: MVTec ITODD and T-LESS for industry settings and consider desirable features for 3D model dataset for robotic nuclear decommissioning. Due to the limit of accessible data, the focus is on the reactor vessel components.

2. Reactor Vessel Components

The reactor vessel and its internals contain the heat source for the nuclear steam supply system in the form of the fuel assemblies in the core area. The cladding of the fuel assemblies provides the first barrier to the release of fission products to the environment. The fuel assemblies are supported and held in alignment by the internals packages within the reactor vessel. The internals packages provide flow paths for the coolant to remove the heat from the fuel and distribute it to the coolant loops for circulation [2].

The reactor vessel is a shell that contains the reactor internals and core, which is composed of (1) cylindrical wall and welded hemispherical bottom, and (2) removable hemispherical upper head. The electromechanical control rod drive mechanisms (CRDMs) and incore temperature instrumentation supports are attached to the reactor vessel head. The bottom of the vessel contains penetrations for the incore nuclear instrumentation. All penetrations are welded to their respective head to minimize coolant leakage

The reactor vessel contains reactor core and reactor internals. The reactor internals are comprised of upper support structure, lower core support structure, and in-core instrumentation support structure. The internals are designed to support, align, and guide the core components; direct coolant flow to and from core components; and guide and support the incore instrumentation.

The taxonomy (i.e. hierarchical list-up) of reactor vessel components is as follows:

- Reactor Vessel
  - Wall
  - Bottom
  - Head
    - Control rod drive mechanism
    - Rod travel housing
    - Instrumentation port
    - Thermal sleeve
    - Lifting lug
    - Closure head assembly
    - Hold-down spring

- Reactor Internals
  - Upper support structure
    - Upper support assembly
    - Upper support column
    - RCCA guide column
    - Thermocouple column
    - Upper core plate
  - Lower core support structure
    - Core barrel
    - Core baffles
    - Lower core plate
    - Lower core support column
    - Neutron shield pad
    - Specimen holder
    - Lower core suport plate
  - In-core instrumentation support structure
    - Upper system
    - Lower system

3. Existing Industrial 3D Model Datasets

MVTec ITODD is a dataset for 3D object detection and pose estimation with a strong focus on industrial settings and applications. It contains 28 objects arranged in over 800 scenes and labeled with their rigid 3D transformation as ground truth. The scenes are observed by two industrial 3D sensors and three grayscale cameras, allowing to evaluate methods that work on 3D, image, or combined modalities. The dataset's creators from MVTec Software GmbH have chosen to use grayscale cameras because they are much more prominent in industrial setups.

The objects were selected such that they cover a range of different values with respect to surface reflectance, symmetry, complexity, flatness, detail, compactness, and size.

For each object, scenes with only a single instance and scenes with multiple instances (e.g., to simulate bin picking) are available. Each scene was acquired once with each of the 3D sensors, and twice with each of the grayscale cameras: once with and once without a random projected pattern.

Finally, for all objects, manually created CAD models are available for training the detection methods. The ground truth was labeled using a semi-manual approach based on the 3D data of the high-quality 3D sensor.

T-LESS is a new public dataset for estimating the 6D pose, i.e. translation and rotation, of texture-less rigid objects. This dataset includes 30 industry-relevant objects with no significant texture and no discriminative color or reflectance properties. Another unique property of this dataset is that some of the objects are parts of others.

Researchers behind T-LESS have chosen different approaches to the training images and test images. Thus, training images in this dataset depict individual objects against a black background, while test images originated from twenty scenes with varying degree of complexity. Here are the examples of training and test images

4. Strategy for Reactor Vessel 3D Model Dataset

The 3D model dataset will include a rich set of annotations that provide semantic information about those models, establish links between them, and links to other modalities of data (e.g., images). These annotations are exactly what make the 3D model dataset uniquely valuable.

Language-related Annotations: Naming objects by their basic category is useful for indexing, grouping, and linking to related sources of data. We can organize the dataset based on the WordNet taxonomy. Synsets are interlinked with various relations, such as hyper and hyponym, and part-whole relations. Due to the popularity of WordNet, we can leverage other resources linked to WordNet such as ImageNet, ConceptNet, Freebase, and Wikipedia

Geometric Annotations: A critical property that distinguishes 3D model dataset from image and video datasets is the fidelity with which 3D geometry represents real-world structures. We can combine algorithmic predictions and manual annotations to organize shapes by category-level geometric properties and further derive rich geometric annotations from the raw 3D model geometry.

Rigid Alignments: Establishing a consistent canonical orientation (e.g., upright and front) for every model is important for various tasks such as visualizing shapes, shape classification and shape recognition. Fortunately, most raw 3D model data is by default placed in an upright orientation, and the front orientations are typically aligned with an axis. This allows us to use a hierarchical clustering and alignment approach to ensure consistent rigid alignments within each category

Parts and Keypoints: Many shapes contain or have natural decompositions into important parts, as well as significant keypoints related to both their geometry and their semantics. For example, often different materials are associated with different parts.

Object Size: Object size is useful for many applications, such as reducing the hypothesis space in object recognition.

Functional Annotations: Many objects, especially manmade artifacts such as furniture and appliances, can be used by humans. Functional annotations describe these usage patterns. Such annotations are often highly correlated with specific regions of an object. In addition, it is often related with the specific type of human action.

Functional Parts: Parts are critical for understanding object structure, human activities involving a 3D shape, and ergonomic product design. We plan to annotate parts according to their function — in fact the very definition of parts has to be based on both geometric and functional criteria.

Affordances: We are interested in affordance annotations that are function and activity specific. Examples of such annotations include supporting plane annotations, and graspable region annotations for various object manipulations.

Physical Annotations: Real objects exist in the physical world and typically have fixed physical properties such as dimensions and densities. Thus, it is important to store physical attribute annotations for 3D shapes.

Surface Material: We are especially interested in the optical properties and semantic names of surface materials. They are important for applications such as rendering and structural strength estimation.

Weight: A basic property of objects which is very useful for physical simulations, and reasoning about stability and static support.

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[2]Westinghouse Technology Systems Manual_RVI