Development of a Cuboidal Fitting Module for Automated Substation Maintenance Robotics

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***Abstract*—This paper presents an innovative method for automating the inspection of electrical substations, with a specific focus on precise boundary detection for rectangular enclosures within substations. The proposed approach utilizes cuboidal primitives to approximate object boundaries, incorporating RGBD sensor data and YOLOv8 object detection. The process involves extracting point cloud data and employing a two-step procedure for orthogonal axis determination, followed by the extraction of key points for approximating the objects with cuboidal primitive. Visual results showcase the method's adaptability across diverse box configurations. While demonstrating robust performance in straightforward scenarios, challenges in complex environments serve as inspiration for future enhancements. The proposed pipeline, designed with potential ROS integration, lays the foundational framework for advancing systems dedicated to efficient substation maintenance.**

***Index Terms*—Cuboidal shape fitting, Image Segmentation, Point Cloud, sub-station monitoring, robotics**

I. Introduction

With the ongoing trend of urbanization, the demand for electricity has witnessed a significant surge. As urban areas expand rapidly, it becomes imperative to extend the network of electrical grids to efficiently transmit electricity to newly developing and expanding regions. Electrical grids play a crucial role in the power distribution process, comprising power stations strategically located near energy sources, electrical substations responsible for voltage regulation, electric power transmission to cover long distances, and electric power distribution to individual consumers, where voltage is adjusted to the required service levels. The transmission of power from the source to the consumer often involves multiple voltage transformations. Substations, an integral component of electrical grids, are responsible for transforming voltage from low to high (step up) and from high to low (step down). As urban areas grow, the need for more power grids and, consequently, more substations becomes evident. These substations are pivotal in ensuring a seamless flow of power to consumers. To guarantee uninterrupted power services, periodic inspections of all components of the electrical grid are crucial to identify and address potential faults before they lead to disruptions in the power supply chain.

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(a) (b)

Fig. 1: A human operator maneuvers the sensor along the periphery of the rectangular closet to identify any potential partial discharge leakage.

With the advancement in technology, robotics solutions are adopted for the regular maintenance of electrical grids. Examples include a robotic system for live maintenance of a 10kV overhead line [1], a dual-arm collaborative robotic system for high-voltage live work [2], and an all-weather robotic system for regular substation maintenance [3]. The use of robotic systems in power grid maintenance has been prevalent for some time, with comprehensive surveys available in [4]–[6].

Our ongoing research is focused on the development of a specialized robotic system specifically designed for the maintenance of electrical substations. These substations are characterized by a series of rectangular enclosures as shown in Fig.1a, and a critical aspect of the inspection process involves the identification of partial charge leakage within these units. Traditionally, this inspection task is carried out manually, requiring the guided movement of a sensor measuring partial discharge (Fig.1b) along the perimeters of the rectangular enclosures. To automate this process, our robotic system must possess highly accurate boundary detection capabilities for the enclosures and be capable of executing precise motions to guide the sensor along the periphery effectively. This involves the integration of advanced sensing technologies and motion control algorithms to ensure efficient and accurate substation inspection.

In the pursuit of automating the detection of boundaries for rectangular objects within the context of our specialized robotic system for substation maintenance, one approach involves approximating these objects with primitive shapes, such as rectangles in a two-dimensional (2D) space or cuboids in a three-dimensional (3D) space [7]. By employing this strategy, the robotic system leverages geometric modeling to represent the boundaries of the rectangular enclosures. In 2D, the use of rectangles simplifies the representation of the enclosure's perimeter, while in 3D, cuboids provide a more comprehensive representation, accounting for the spatial dimensions. This approximation methodology not only facilitates efficient boundary detection but also streamlines subsequent motion planning for guiding the sensor along the periphery of the enclosure. Employing geometric primitives allows for precise calculations and reduces computational complexity, enabling the robotic system to navigate the contours of the rectangular objects with a high degree of accuracy.

In this paper, we introduce our cuboidal fitting module designed specifically for known rectangular objects. We elaborate on our methodology and present the outcomes of its application to a diverse set of known rectangular objects, considering different configurations such as close proximity and random arrangements. Furthermore, we evaluate the robustness of our method through testing on various object types. While our method is currently in the early stages of development, the insights shared in this paper serve as the groundwork for a more advanced model fitting module, which in the future will be deployed on the robotic system for the task of substation monitoring.

II. Literature Review

The literature review provides a comprehensive exploration of recent advancements in approximating objects using shape primitives, emphasizing several benefits inherent to this approach. Noteworthy advantages include addressing challenges such as missing point cloud or absent parts of the target object [25]. Shape primitives offer a simple and parametric representation of objects, requiring fewer memory resources and parameters [24]. This parametric representation is versatile, finding applications in tasks such as 6D pose estimation [26] and determining optimum grasp poses for robotic manipulation.

The studies highlighted in the review showcase diverse methodologies and applications. Notably, in works like [9], [11], [12], authors leverage RGBD data to approximate objects with shape primitives and subsequently calculate optimal grasping poses for robotic manipulation. In [13], a Deep Neural Network is trained for object segmentation into shape primitives, aiding in identifying optimal grasp poses. The study in [14] simplifies novel objects into basic shape primitives like ellipses, utilizing Fuzzy Gaussian mixture models for shape approximation and determining optimal grasping regions.

Additional contributions include a supervised learning approach in [15] for approximating 3D complex object representations with cuboidal primitives, while [16], [17], [20] presents an unsupervised learning method for complex objects using cuboidal primitives. In [18], [19], a supervised learning-based method is introduced for approximating point cloud data with multiple shape primitives.

Moreover, research by [21] enhances robotic manipulation through real-time recognition of elliptic shape primitives, particularly for cylindrical objects. Similarly, [22] proposes a fast and accurate method for recognizing robotic grasps using improved graph segmentation, morphological image processing, and a random forest model. Additionally, [23] introduces a method for creating candidate grasping rectangles based on form approximation, utilizing K-means, a minimal oriented bounding box algorithm, and a LightGBM classifier.

Together, these studies contribute significantly to the diverse landscape of approximating objects with shape primitives, showcasing their applicability in real-world scenarios across various domains.

III. Model fitting Method

To advance toward the development of an automated robotic system for substation inspection, it is essential to accurately estimate the boundaries of the rectangular enclosure. Our approach involves approximating objects using cuboidal primitives, a method that simplifies the boundary estimation process. The visual representation of our methodology can be found in Fig. 2.

Our method takes raw images (labeled as *Raw Image*) and their corresponding registered raw point cloud data (labeled as *Raw PCD*) as input. These datasets are obtained using an RGBD (Red, Green, Blue, Depth) sensor, specifically the Intel Real Sense D435I, which provides RGB images at a resolution of 640x480 and synchronized point cloud data.

In the first phase of our method, the RGB image is fed into the YOLOv8 [10] object detector. This detector is specifically trained to segment the white rectangular boxes, resembling the rectangular closets typically found in substations. The output from YOLOv8 is a segmentation mask, visualized in Fig. 2 and labeled as *Predicted Masks*.

Following the YOLOv8 output, which provides a segmentation mask, and utilizing the registered point cloud data, we

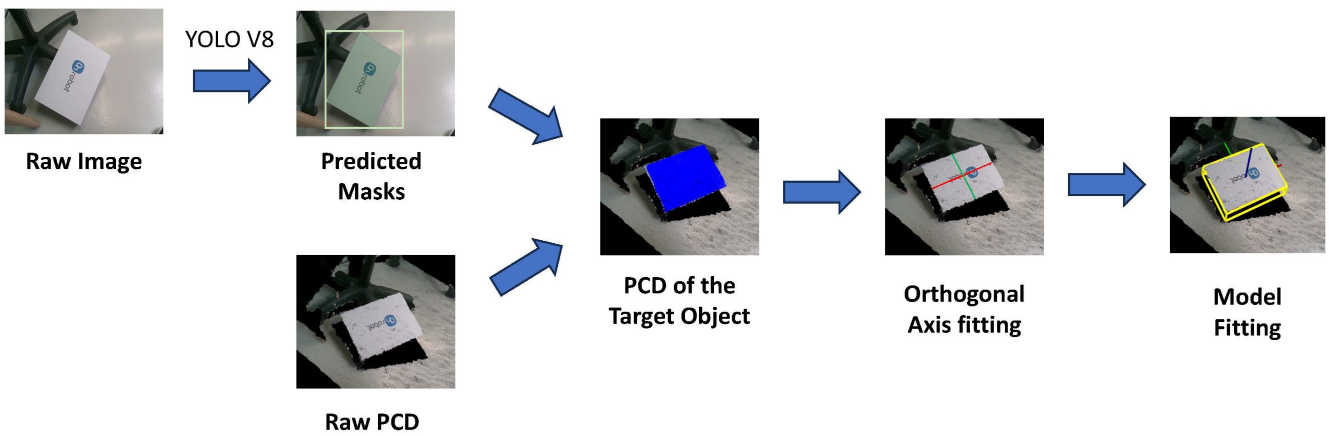


Fig. 2: The proposed method of model fitting

proceed to extract the point cloud corresponding to the target object, referred to as *PCD of the Target Object*. The subsequent steps of our methodology involve approximating this point cloud data using cuboidal primitives. The dimensions of the cuboid are predefined based on the known dimensions of the white box identified by the YOLOv8 object detector. This process is crucial for accurately representing and analyzing the identified target object in the substation environment.

In the next stage, we focus on determining the orthogonal set of axes for the *PCD of the Target Object*. To compensate for the inherent noise in the point cloud generated by the sensor, we adopt a two-step process:

1) Approximation of the visible face with 2D Planar Surface:
   - Utilize the RANSAC (Random Sample Consensus) [27] method to approximate the Point Cloud Data (PCD) with a 2D planar surface.
   - This step effectively filters out noisy points with significant deviations from the planar surface, leaving behind inliers.
2) Finding Orthogonal Axes for Inliers:
   - Once the inliers are identified, we proceed to find the optimal set of orthogonal axes.
   - The objective is to determine the minimum area rectangle covering all the inliers.
   - The process involves randomly selecting one set of orthogonal axes, ensuring that the formed rectangle covers all inliers, and calculating the area of the rectangle.
   - The procedure is repeated iteratively, with each repetition aimed at finding another set of orthogonal axes. The iteration continues until the minimum area rectangle is found, and the corresponding set of axes is deemed the optimal orthogonal axis.
   - The detailed procedure for our orthogonal axis finding method and its convergence is documented in our previous work [9].
   - A representation of one such optimal orthogonal axis set is illustrated in Fig. 2 and labeled as *Orthogonal Axis fitting*.

Upon successfully determining the orthogonal set of axes, we extract crucial information from the analysis:

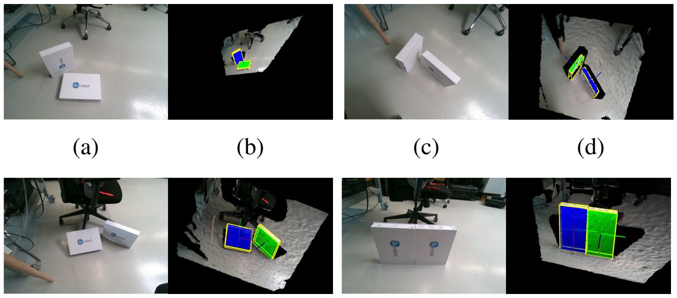
1) Extraction of 5 Key Points:
   - The two extreme or end points of each orthogonal axis.
   - The intersection point of the two axes.
2) Identification of Cuboidal Object Face:
   - The length measurement along each orthogonal axis enables the identification of the face of the cuboidal object under observation.
3) Pose Estimation of Cube Model:
   - Utilizing the correspondence between these five points in the local cube model and their counterparts in the camera frame.
   - With this correspondence, we can accurately estimate the pose of the cube model in the camera frame [8].
   - The resulting pose estimation is illustrated in Fig. 2 and labeled as *Model fitting*.

This final step encapsulates the extraction of key geometric features and the determination of the pose, providing a comprehensive representation of the cuboidal object identified in the substation environment.

IV. Experiments

In this section, we present visual results showcasing the performance of our approach across various box configurations. Recognizing that rectangular closets in substations are often positioned adjacent to each other, our method was evaluated on both random box configurations (Fig.3b, Fig.3d, Fig.3f) and configurations with adjacent boxes (Fig.3h).

Given that the dimensions of rectangular closets in substations are significantly larger than the white boxes used



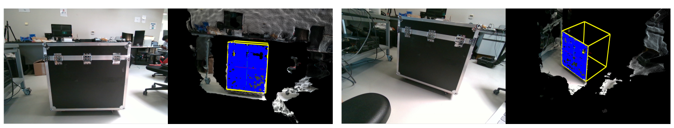
(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 3

for training, we conducted robustness tests by evaluating our pipeline on larger boxes, thereby demonstrating its model fitting capability.

To test our method on new objects, we conducted training on a YOLOv8 model using a customized dataset of target objects. This dataset consisted of raw images paired with manually labeled segmentation masks. Training continued until the desired level of accuracy was achieved, and subsequent testing on new objects produced results as shown in Fig.4b and Fig.4d.



(a) (b) (c) (d)

Fig. 4

It's crucial to emphasize that our proposed pipeline is designed for future integration into robotic systems. The entire module operates as a service client-based system over ROS (Robot Operating System), ensuring a smooth integration with robotic platforms in the future. This design choice enhances the adaptability of our approach for practical implementation in robotic inspection systems.

Additionally, it is worth noting that the proposed method demonstrates satisfactory results in relatively straightforward configurations, such as cases where rectangular objects are clearly visible, or only one face of a rectangular object is prominently displayed, or when objects are centrally positioned in the frame. However, challenges arise in more complex scenarios where objects are partially visible, full faces are not visible, or multiple faces are visible. Addressing these challenges will enhance the robustness of our method. The proposed method serves as the foundation for future improvements, providing a solid base for developing more robust and versatile solutions.

V. Conclusion

In conclusion, our proposed cuboidal fitting module represents a crucial step toward the development of an automated robotic system for substation maintenance. By leveraging geometric primitives, specifically cuboids, our method facilitates accurate boundary estimation of rectangular enclosures within substations. The integration of YOLOv8 for object detection, as well as optimal orthogonal axis estimation, forms the foundation of our approach. The experiments showcase the versatility of our method in handling various box configurations, including adjacent arrangements and larger boxes. While the current implementation demonstrates success in simpler scenarios, challenges persist in more complex situations. Addressing issues where objects are partially visible or multiple faces are in view is crucial for enhancing the method's robustness. While the method is in its early stages, the insights gained lay the groundwork for future advancements, promising a more robust and versatile solution for the automation of substation maintenance tasks.

VI. Future Plan

The presented model fitting algorithm is a two-step procedure. Firstly, the image is fed to the custom-trained YOLOv8 in order to segment the target object. Then in the second step, corresponding point cloud data is processed and approximated with the cuboidal model. The approximated model can help us to calculate the boundaries of the rectangular boxes.

Our next step involves integrating this advanced algorithm into a Franka Emika panda manipulator mounted on a Jackal UGV. This integration will result in a versatile mobile robot capable of navigating across various substation panels, which typically exhibit rectangular shapes. Equipped with a partial discharge measurement sensor, the end effector of the Franka Emika panda will enable the robot to autonomously detect charge leakage along the boundaries of rectangular closets commonly found in substations.

By combining these technologies, our plan aims to create a sophisticated robotic system capable of autonomously navigating [28], [29], analyzing, and assessing specific parameters across different panels within substations. This advancement is expected to significantly enhance efficiency in monitoring and maintenance processes, ultimately contributing to safer and more reliable substation operations.

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