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Point cloud based robot cell calibration

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ABSTRACT

This paper presents a method to automatically calibrate an articulated robot arm using measured point cloud data. The method captures the inner structure of complex engineering objects from measured datasets. In the developed workflow first the point cloud is segmented, and then the CAD models of the objects in the work cell are recognized and fitted onto the segmented point cloud. To boost the computational efficiency of the method, parallelization was performed by applying general-purpose programming of the graphics processing unit. In this paper the calibration of a UR5 robot is carried out using measured data of a Kinect sensor.

1. Introduction

Collaborative robot cells are gaining increasing importance as a new type of work environment where operator and robot work together in a fenceless environment. The flexibility of these cells however relies on accurate digitalized knowledge of the environment and the operator, which is the base of reliable and safe supervision systems and advanced control of the cell. This accurate digitalized environment can be determined by calibrating the reference digital (CAD) models to the real environment using measured data. Maintenance, repair and overhaul (MRO) activities also require an accurate model of the complex engineering object [1].

Robot calibration is a well researched topic that deals with the differences of the CAD reference and the real world. One type of calibration calculates and compensates the joint errors and the link's geometric dimensions to ensure precise positioning. The calculation of the transformation between a reference coordinate frame and the local coordinate frame of the robot to be calibrated is also considered as robot calibration. The former is a relatively well researched topic [2–5]. The latter, on the other hand has fewer references. As the robots have to be calibrated with respect to an outer reference frame, usually cameras are used. Watanabe et al. [6] proposed a method for accurate setting of workpiece using CCD cameras. Arai et al. [7] also used CCD cameras to set the position of a second robot relative to another robot already set up. Common drawbacks of these methods are that they take too much time to run, depend on human intervention, and they may also require external markers.

In this paper our intention is to introduce a method, with an incomplete point cloud acquired with a fixed 3D camera, with no markers on the calibrated robot, assuming only the possession of the CAD geometry of the robot. To speed up the process we utilize general purpose programming of the GPU.

2. Problem statement

A collaborative robot cell with a 3D depth sensor mounted at a fixed position, and the virtual scene of the robot cell as a CAD assembly model are given. This virtual scene is the so-called *as-designed* model of the robot cell. The depth sensor captures the environment of the robot cell as a point cloud. The point cloud is considered to be the partial measurement of the so-called *as-built* model of the cell. The coordinates of the points are defined in the *point cloud reference frame*, which is located at the focal point of the sensor (Fig. 1).

This paper looks at the robot cell calibration as the crucial step to determine the *as-built* model of the robot cell. The *as-built* and *as-designed* models might differ because of various reasons such as difficult modelling features like cables and small accessories what

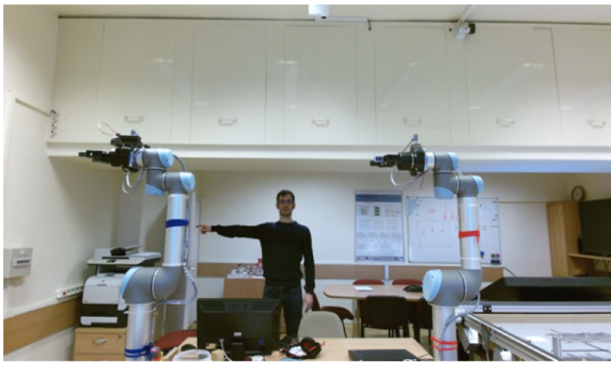

Fig. 1. Robot cell from the viewpoint of the Kinect sensor.

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might be omitted from the *as-designed* model. Similarly, changes made during the construction process may result in deviations from the intended design.

In order to determine the difference between the *as-designed* and the *as-built models*, they have to be compared in a common reference coordinate frame.

Cell calibration assumes that the depth sensor is placed to a fixed position in the cell and no calibration artefacts are used. The fixed position of the depth sensor implies that only partial measurement could be obtained, because of occlusion and shadowing.

It is also assumed that the virtual scene models are the only important objects of the robot cell, therefore the *as-designed* and *as-built* models might differ considerably, because of the non-modelled artefacts in the robot cell.

The result of the calibration is the alignment transformation that transforms the *as-built model's* reference coordinate frame (i.e. point cloud's reference frame) to the *as-designed model's* reference frame (CAD reference frame of the model), realizing the *calibrated workcell model.*

3. Workflow of robot cell calibration

A *workflow* has been developed (see on Fig. 2) for calculating the alignment transformation based on the point cloud measurement and the CAD model of the work cell.

The basic idea of the algorithm is to localize one or more *frame features* on the measured point cloud and the reference CAD scene, respectively, and to calculate the transformation between these two frames. The *frame feature* is a geometric feature that provides means to attach a local coordinate frame. For example an Axis Aligned Bounding Box (AABB) is such a type of frame feature, because a local coordinate frame can be naturally bound to a rectangle (see Fig. 4). Since frame feature localization in a CAD model is straightforward—basically equivalent to sub-assembly selection—, *frame feature* selection in the point cloud is considered further.

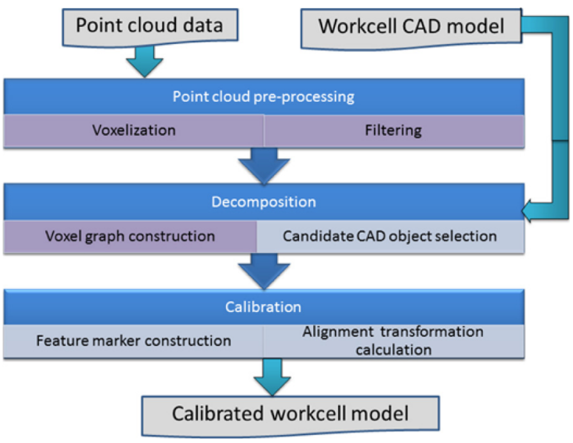

Fig. 2. Workflow of the cell calibration process.

3.1. Point cloud pre-processing

The process starts with *voxelization*, which takes the point cloud and calculates the position of those voxels—with given dimensions—that contain at least one point. Furthermore, voxels with low point density are filtered out as measurement errors. The threshold of the filtering process is also an input parameter. Next, the connectivity of the neighbouring voxels is also calculated as an ordered pair of voxel index. These edge lists will define the so called *voxel connectivity graph* (*VCG*). Fig. 3 display the VCG of the robot cell.

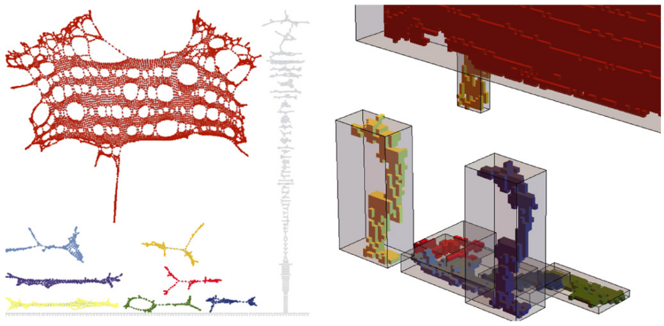

Fig. 3. Connected voxel subgraphs of the VCG of the robot cell and the corresponding voxel set and AABB rendering.

3.2. Decomposition

The goal of the decomposition phase is to localize a disjoint, connected set of points that might correspond to a given reference candidate CAD component. The underlying idea of decomposition phase is that the connected voxel subgraphs represent relevant components of the robot cell, which could also be identified in the virtual CAD scene as a component or subassembly.

The connected subgraph of the VCG graph is calculated with the standard union-find algorithm. Using the connected subgraphs of the VCG, the disjoint, connected sets of points are calculated together with their AABB (see Fig. 3). The candidate CAD object is selected as the geometry of the robot model (see Fig. 4), while the localizing feature vector is defined based on the AABB of the geometry.

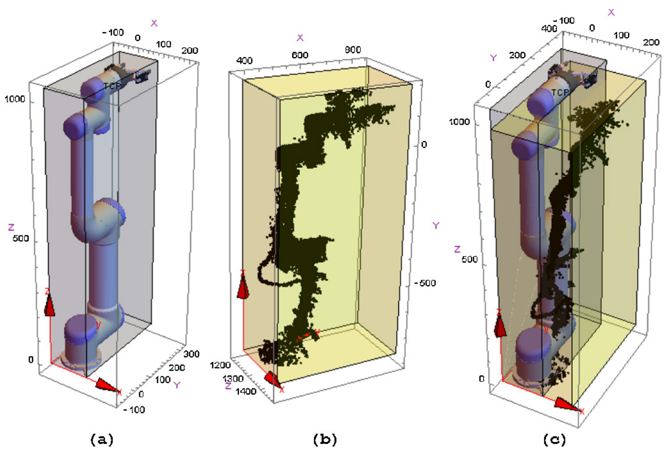

Fig. 4. AABB of CAD model (a) AABB and points of a connected subset (b) aligned connected subset and CAD model (c).

This localizing feature vector is defined as the normalized AABB dimension that is given in turn by the sorted (*length*, *width*, *height*) values of a box. The values for the candidate CAD reference object (see Fig. 4a) are as follows:

$$reference \rightarrow \{155.187, 415.36, 1042.63\}$$

The normalized AABB dimensions are also calculated for the indexed disjoint connected sets of points as follows:

$$\begin{array}{ll} 1 \rightarrow \{357.00, 1307.00, 3997.00\}, & 2 \rightarrow \{295.00, 499.10, 988.70\} \\ 3 \rightarrow \{264.00, 470.80, 975.10\}, & 4 \rightarrow \{138.40, 469.00, 886.90\}, \\ 5 \rightarrow \{52.66, 352.00, 688.00\}, & 6 \rightarrow \{112.00, 256.50, 514.30\}, \\ 7 \rightarrow \{108.20, 448.00, 476.20\}, & 8 \rightarrow \{148.70, 322.50, 535.00\} \end{array}$$

The candidate object detection finds the index of the disjoint connected set of points whose feature vector is the closest to the reference feature vector using the *chessboard* distance function. In case the robot cell contains more than *n* identical robots than the first *n* closest AABB indices are looked for. In given example it is disjoint connected set 2 and 3.