Robotic Plug-in Combined Charging System with Improved Robustness †

Josef Cernohorsky and Pavel Jandura *

Technical University of Liberec, Faculty of Mechatronics, Informatics and Interdisciplinary Studies, Institute of Mechatronics and Computer Engineering, Liberec, CZ46117, Czech Republic; josef.cernohorsky@tul.cz

* Correspondence: pavel.jandura@tul.cz; Tel.: +420-48-535-3861

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Abstract: This paper describes the development of an algorithm robotic plug-in of a charging system for mobile platform. In the first chapter, there is a short overview of possibilities of automatic plug-in system, including proprietary industrial solution. In the main part, there is a description of the system based on UR robot with build-in force torque sensors and Intel RealSense Camera. This camera combines IR depth lens with regular RGB camera and six DOF inertial sensor, which is used in our application too. The conventional solution of this problem is usually based on RGB image processing in various state of the art, from simple pattern matching, neural network, or genetic algorithm to complex AI solution. The quality of the solution mostly depends on robustness of image processing. In our cases, we use simple sensor fusion. Thanks to multiple information and constrain of values, we can assume, if the algorithm is proceeding successfully or not. The system uses the internal parameters of the robotic arm, e.g., end-effector position and orientation and force-torque information in tool center point. The next information is RGB camera image and camera depth image, and the inertial unit build in camera. The other important information is the location of the vehicle inlet on the mobile platform, where the shape of mobile platform is considered as a constrain for image processing. The system is validated only on a physical model with CCS type 2 plug and vehicle inlet, because the mobile platform is under construction by another team.

Keywords: image processing; sensor fusion; robotic system; pin-in-hole problem

1. Introduction

The autonomous mobile platforms will be more and more common for interoperation logistics [1,2]. The key feature on how to reach a high duty cycle of the battery powered platform is the use of the high power charging (HPC) system [3] or battery swapping station [4]. Most of the platforms use proprietary solution for charging [5], mostly because a standardized automatic connection device underbody (ACDU) interface [6] is still not available. However, thanks to the HPC systems, now widely expanding in public charging infrastructure for on-road vehicles, the use of standardized solution makes sense. The disadvantage of this standardized solution is that the used combined charging system (CCS) type 2 [7] is not designed for autonomous robotic handling but rather for human service.

2. Quick Overview of Possible Solution

We concerned ourselves only with the robotic plug-in charging system, because battery swap needs an additional infrastructure and floor space.

The localization of the mobile platform can be handled by sensor fusion of several different sensor principles [8,9]. Typically, odometry, nine DOF sensor, combines accelerometers, gyroscopes and magnetometers, GPS or ultra-wideband (UWB) absolute localization [10], and even advanced visual systems. This attitude is not discussed in the paper. The typical outputs of this localization system are not precise enough to reach a charging connector without additional localization system or mechanical guidance.

3. Materials and Methods

For our experiment, we use a dummy model of the CCS type 2 plug and the vehicle inlet. The UR3 robot is suitable as a low power variant and an Intel Realsense D435i camera was used. MATLAB was selected as the development environment. The camera was steady, not on a robotic arm, but in the future it can be changed. The basic camera image is in Figure 1.
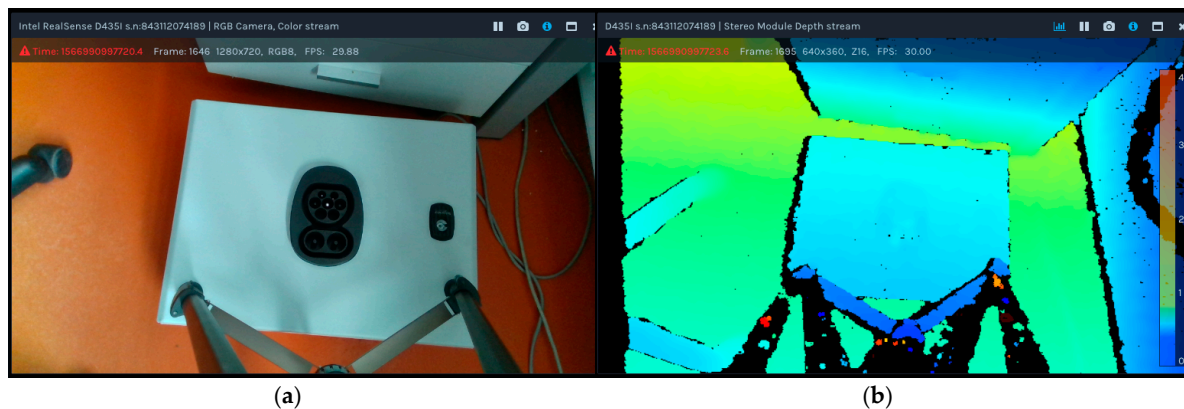

(**a**)   (**b**)

Figure 1. Basic (raw) capture from Intel RealSense D435i camera. (**a**) Standard picture; (**b**) depth image (both pictures obtained by RealSense Viewer).

4. Results

The problem can be separated into two sections, the results of image processing, which provide the position and orientation for the second part, which is the robotic control.

4.1. Image Processing

The data is provided through SDK by a single array, so it must be restructuralized to (m-n- …) in MATLAB to display the image. Thanks to a known camera distance from inlet Figure 2a, we can filter depth data to get the X-Y plane of the cabinet, Figure 2b.
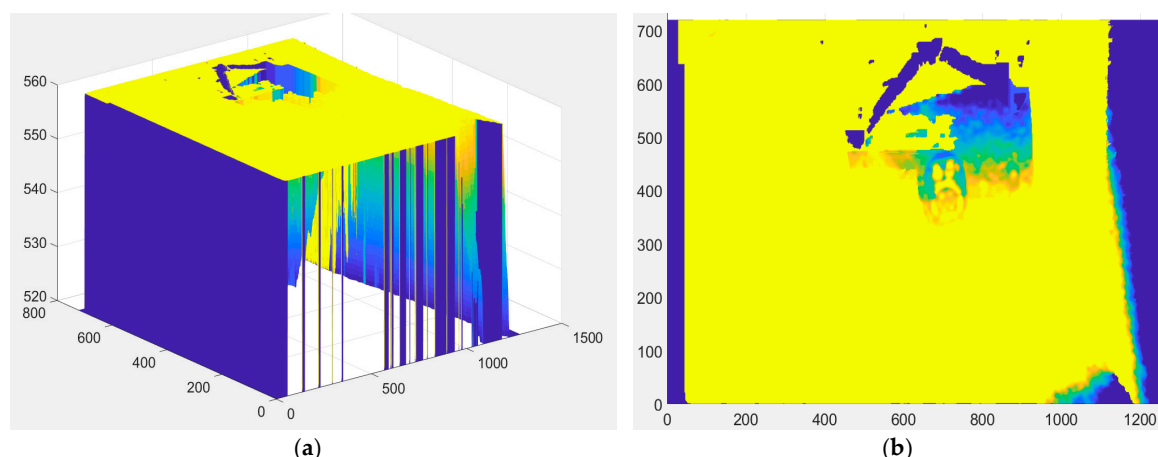
Figure 2. Depth data in the distance of 520–560 mm from the camera. (**a**) Shows nice "candidate valley" where the inlet should be found; (**b**) shows data where the inlet is barely visible and includes the IR scanning relics.

The inlet recognition is based on a visible image pattern matching, depth camera information verification that improves the robustness of the solution. The main point is in the visible image processing, where thanks to the elliptical shape of the CCS inlet we find the area with proper contour and size, results are displayed in Figure 3.
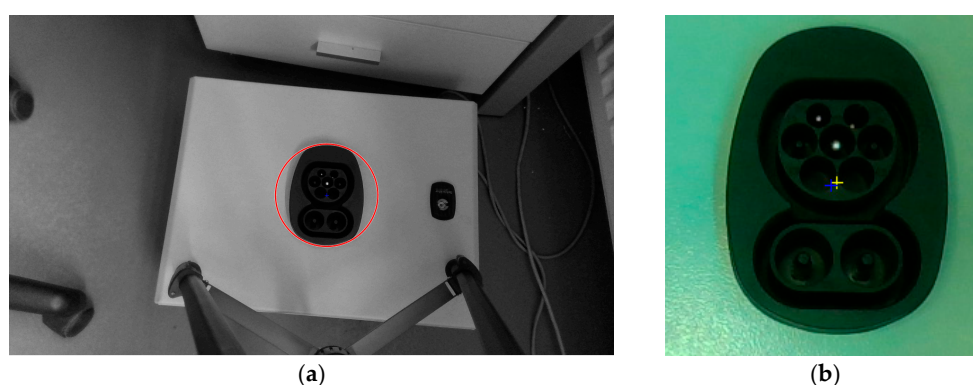

Figure 3. Visible image processing: (**a**) Basic circular detection of the inlet; (**b**) two center points based on elliptical detection (yellow is more accurate).

The center point is reliably detected; the blue one was based on a different algorithm, where the shadow slightly influences the position. From the optical image, we therefore get the center point and orientation of the object.

The next level of image processing is pattern matching, where preimage is labeled and then found in the picture, Figure 4. We have to say, that this algorithm really depends on sensitivity setting for labeling. This algorithm is iterative, when the center point is detected out of the depth region, the results are wrong and the sensitivity is adjusted and algorithm is started again, five times maximum.
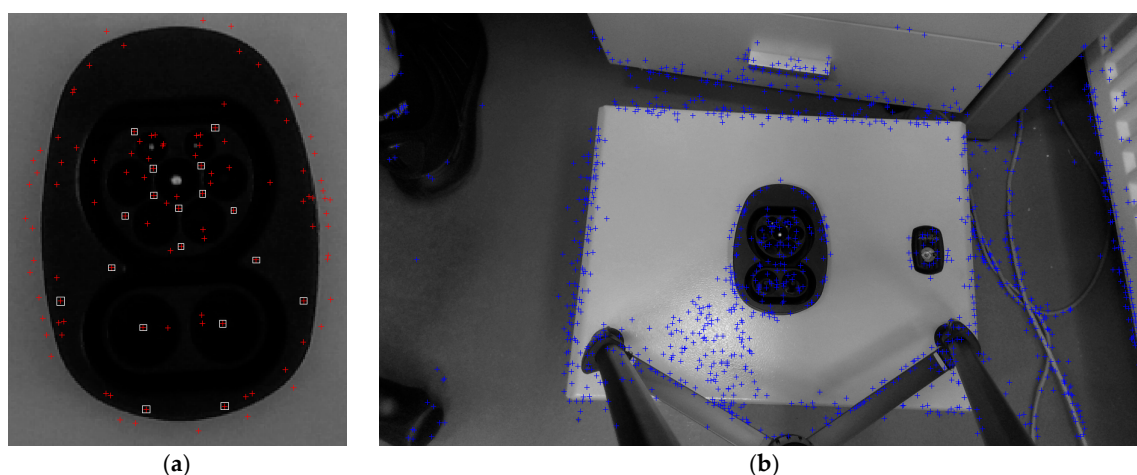
<div align="center">(a)   (b)</div>

Figure 4. Featured extraction on "plain black". (**a**) White markers highlight the significant natural points, centroids of surfaces, close section on pinholes, etc.; (**b**) glitter on cabinet plane and inlet with markers to pattern match.

4.2. Robotic Control

The robotic control is based on TCP/IP communication, where the tool of CCS type 2 plug is set up on the robot. Input data are the center point and Z-tool rotation orientation, the output data are six DOF force and torques measured by the robot. Before first use, a simple camera calibration must be done, where the pairs of camera point and robotic coordinates are matched together by affine transformation. The plugging process is separated into several steps.

- "Reaching the first contact" (orientation of tool Z-tool axis rotation is not compensated). The position setpoint is above the plane and the robot moves to Z-tool axis force threshold.
- "Force controlled motion" (adjustment of position X-Y plane to minimize tangential forces).
- "Partial plug-in" (Z-tool rotation from positive torque threshold to negative torque threshold and setting the orientation to half between those limits.)
- "Finalization of plug-in" to reach the proper depth from initial contact to ensure the full plug-in. This operation must be made within force torque limits, to ensure proper orientation in X, Y axis.

Those steps are nowadays realized in MATLAB, thanks to faster software development, but for the final stage they will be implemented into the robotic controller for simplification of control process.

5. Discussion

The image processing uses several approaches on how to detect the CCS type 2 vehicle inlet. The depth information is used as "candidate valley" for verification. For final realization, it seems the "eye on hand" arrangement is better. The mandatory enhancement must be made for lighting, since daylight and fluorescent ambient lighting (for worst case study of the algorithm) were used for our experiment. The improvement in lighting helps to feature extraction on the inlet and can significantly improve the pattern matching.

The last problem is in force torque control during plug-in operation, where the end effector force torques are reconstructed from joints values, independent force torque sensor could help, and such solution will be used in further research. The iterative attitude via several tool axis is time consuming, in the future we would like to develop an algorithm to measure the forces and torques and calculate the compensative motion in one-step for all axis.

The important fact is that the recognition algorithm is reliable, there are almost no positive false, the inlet is recognized, but not present. The negative false are typical in case, when part of the inlet is out of range or during bad lighting conditions. This must be improved during the next phase of

research by better lighting and camera on robotic hand arrangement. However, the MATLAB with image processing and robotic toolboxes is a good environment for development.

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