Concept for Automated Robot Programming Using Image Processing

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Abstract. The trend towards customized products and the shortening of product lifecycles leads to changing requirements for production systems. Their flexibilization is focus of different approaches, among others regarding possibilities to alter the mechanical configuration. Within, modularization and robotics serve as key enablers, allowing a flexible composition of plant sections as well as a free manipulation of objects. One major challenge is the adaptive robot programming, especially for free positionable plant modules. This paper presents a modular architecture for offline robot programming based on position measurement via image processing, robot path simulation and a novel concept for data management using asset administration shells for standardized data access and exchange. In particular, the concept for localizing objects via two dimensional data codes is described and evaluated.

Keywords: Reconfiguration · 3D-Image processing · Adaptive control

1 Introduction

Shorter product lifecycles are accelerating the trend towards customized production systems. A crucial factor to adapt production systems to new products is the possibility to alter the mechanical configuration of the production system. Reconfigurability can be achieved through modularization of automation systems. In this case, requirements arise with regard to the mechanical and software integration of automation modules into superordinate control systems. Therefore, concepts for position detection of modules and integration via plug and produce are necessary [1]. As pointed out in [2], autonomous software agents – with the ability to recognise their environment using sensors and to act reactively on it – have a high relevance for mechanical and plant engineering in the coming five to ten years. A self-description of modules can help to implement plug and produce functionality between a subordinate control system and devices. However, in case of mechanical reconfiguration, e.g. when connecting multiple, mobile, free positionable modules, a methodology for geometric calibration of new modules as well as a dynamic simulation system is required. While the workspace of classical production systems consists of active and passive elements, e.g. digitally connected workpiece carrier or offline tool holder, a system is required that is able to

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detect the position of elements that do not have integrated control or communication logic. One possible approach is the position detection of objects using cameras in combination with image processing. When using identification markers the objects can also be connected to a virtual representation, expanding their information value. In order to make an automated production system reconfigurable, the need for a robot calibration system was identified. In a first approach [3], a general concept was presented. The concept allows the detection of module positions and geometrical referencing of laboratory devices after mechanical reconfiguration. Therefore, a camera-based measurement is considered, determining the position of data matrix codes (DMC) on objects in free space.

This paper presents an architecture for reconfiguration related offline robot programming using image processing and simulation. The concept enhances the approach introduced in [3] with a solution for standardized data management using hierarchical asset administration shells (AAS). Additionally, the developed approach for position detection via DMCs is validated in an exemplary production system, a novel modularized and freely configurable automated platform for the cultivation of induced pluripotent stem cells (iPS cells) – the iCellFactory. The platform consists of laboratory devices mounted on modular tables that allow a flexible integration and free positioning on a continuous lab bench. A DMC attached to each module serves as identifier as well as a basis for the geometrical position detection. A gantry-mounted six-axis robot is used to transport laboratory material within the platform. This structure requires a precise detection of module positions as well as a resilient simulation for collision-free path planning.

2 Preliminaries

This section summarizes the related work in the field of robot programming by image processing and the Industry 4.0 component as a basis for the presented architecture.

Robot Programming by Image Processing. Different concepts for robot programming by optical measurements have been set up, allowing pick and place operations of objects utilizing image processing and the learning by demonstration paradigm. One possible and widely used approach is the detection of the object itself and its position, which is used for pick and place operations in small [4] and large scale robot operations [5]. A special challenge is the direct recognition of objects and measurement of their position in front of an inhomogeneous background or mixed with other objects in the visual range. Roshni et al. [6], presents a method to enhance the accuracy of the optical position detection of objects for robot gripping operations, using the object's centre of gravity, allowing an improvement of the optical object detection. Other approaches utilize the imaging of identification codes. The big advantage of these codes is their unambiguous identification and the possibility to store additional information, e.g. QR-codes [7]. Furthermore, some approaches for using codes for position estimation have been presented. E.g. barcodes are used to detect robot gripping positions for cell culture vessels on a flat work surface [8]. Wang et al. [9] presents a method for the optical measurement of relative positions between a camera and a two-dimensional identification code used for navigation in farming. Another promising approach utilizes the artificial code ArUco with OpenCV to localize mobile robots in a two dimensional room [10]. The results indicate the applicability of the ArUco code for position detection, still the accuracy of the system is limited and thereby not usable for industrial robot applications. Besides, today's simulation tools enable a fast estimation of collision free robot paths, allowing a flexible adaption of robot paths to changing environments [11]. Yet, a pervasive concept for combining position measurement with robot path simulations for programming industrial robots is missing. Additionally, current approaches on image processing for robot programming lack in terms of accuracy and robustness, when the camera observes a bigger area.

Industry 4.0 Component. To close the gap between measurement, simulation and control, a continuous data management and processing is required. The Industry 4.0 Component (I4.0Comp) as a specific case of cyber-physical systems allows a description of physical or non-physical entities, e.g. plant module. Therefore, the I4.0Comp extends a real asset by its digital representation. The digital representation is deposited in an asset administration shell (AAS), including property value statements and sub models to describe different properties or functions of an asset [12]. Additionally, the AAS can be used as a container for tracked life cycle data of an asset [13]. By storing all necessary information of an asset, the I4.0Comp serves as a single source of truth.

3 Approach

In order to adapt freely to new mechanical configurations within the production system, an architecture is considered, which primary consists of four main units, shown in Fig. 1. The overall concept is described in the following, focussing on image processing and a novel solution for data management.

Measurement. The main unit 'measurement' describes a framework for image processing based on the concept presented in [3]. A camera system, scanning the workspace of the production system, provides images for further image processing. The framework is separated in two main function parts in order to enable an automatic calibration of new modules and to achieve a fast detection of module positions. Both is done using the same basic algorithms for image processing, including edge detection, DMC decoding and the application of image filters. The first part is responsible for the calibration of new modules, the second for position detection after reconfiguration. Within the calibration, the vector between a reference code, placed in the loading position of the respective laboratory device, and a module code is measured. The measurement setting is shown in Fig. 2. Therefore, a laboratory vessel used for media containment – microtiter plate (MTP) – is equipped with the reference DMC and placed on the loading position of the device. The second DMC with the module code is attached to the module table surface. While no specific positioning is required, preparation time is reduced. After calibration, the distance vector is saved within the corresponding module AAS, being available for the reconfiguration of the virtual module in simulation.

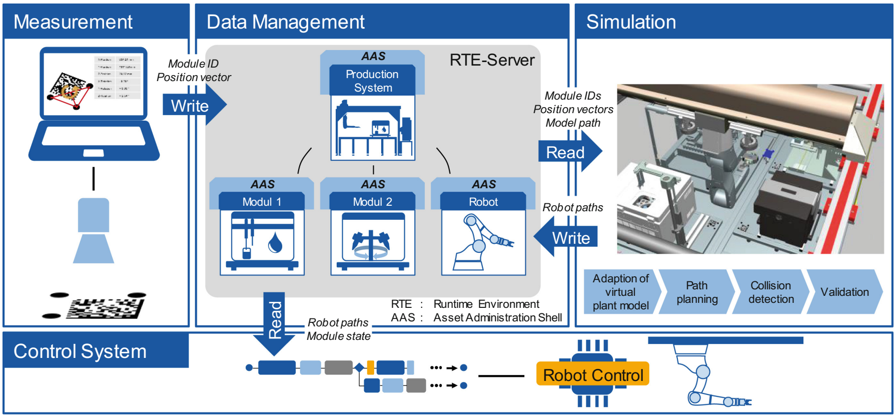

Fig. 1. Architecture for automatic robot programming using image processing and robot path simulation

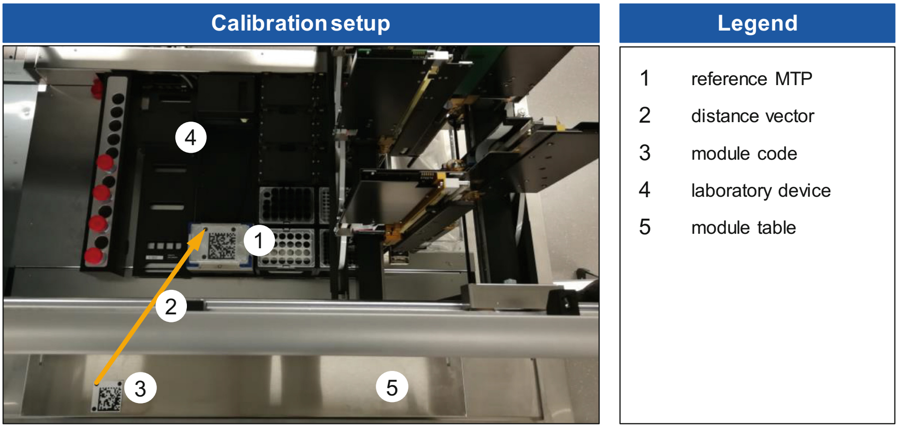

Fig. 2. Exemplary calibration measurement setting for liquid handling unit

In order to get the current module positions, the workspace is scanned for available module codes. Depending on the camera system used, a continuous or a sequential scan is possible. The position and orientation detection has to include six axis of freedom, being able to also detect a module's roll and pitch angle. The image-processing algorithm is split in two sections, position detection and measurement of orientation, as can be seen in Fig. 3. After identification of the DMC, the image size is reduced to a defined region of interest (ROI), allowing a faster processing. Hereafter, the three circles attached to the standard DMC are selected using edge extraction. The x- and y-position of the code is measured by calculating the vector between the optical axes of the camera to the centres of the circles. The z-position is determined using the image equation based on the circle diameter. By adding the relative position of the camera within the workspace, the global position of the DMC is calculated. In a next step, the orientation of the code is calculated.

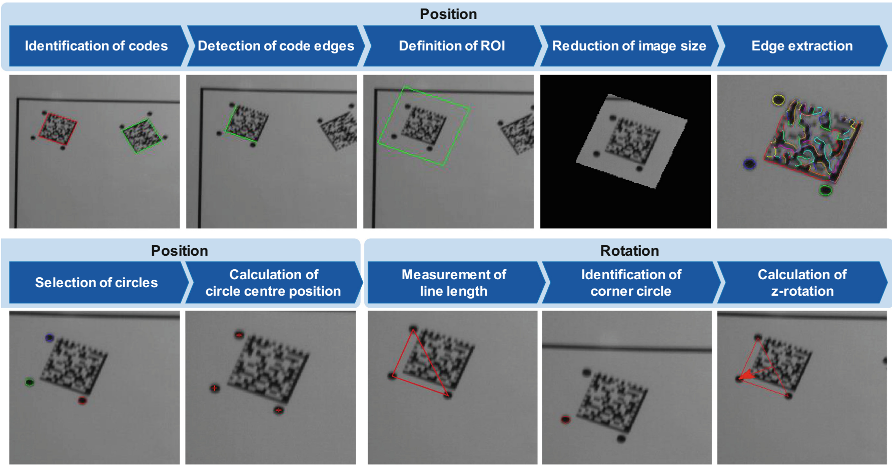

Fig. 3. Image processing sequence for measuring the position and orientation of a DMC in 3D-space

First, the lengths of the lines connecting the three circle centres are measured in order to identify the corner circle. As the circles form an isosceles triangle this calculation is trivial. The vector from the plumb base on the hypotenuse to the centre of the corner circle can be used to determine the z-rotation of the code, relatively to the camera coordinate system. Since the position of all three circle centres in space is known, the plane spanned by the points can be calculated in order to determine the x- and y-rotation of the code. Then the angles between the known x-y-plane of the plant, spanned by the base coordinate system and the calculated plane are determined, returning the x- and y-rotation of the code. The x- and y-rotation is not focussed within the evaluation.

The newly determined position values of the modules are stored as a six dimensional vector in the respective module AAS.

Data Management. Beside their mechanical structure, each element of the production system also has a digital representation. This representation is encapsulated in an AAS, abstractly describing relevant element properties and providing links to additional data, e.g. CAD files, manuals. All AASs are running in a runtime environment implemented on a server, guaranteeing a permanent access to the data. Thereby, one major criterion for Industry 4.0 Components is given. Besides, to enable an unambiguous identification, every AAS has a unique AAS-ID. Due to their characteristics, AASs can also map hierarchical structures, whereby the required abstraction level is made available. For modularized production systems, the system itself as well as its modules can be modelled as AASs. For the considered use case, each module has at least the properties module ID, description, DMC, position, skills and a link to the kinematic CAD model. Furthermore, life cycle data for each production resource can be stored in the AASs, e.g. enabling predictive maintenance.

To enable an automatic robot programming based on new configurations of the production systems measured by the image processing, data has to be exchanged with and forwarded to the involved main units. This supervision of data can be implemented multiple ways. One approach is to implement an external supervisor software module, which tunnels data towards and from the AAS and registers changes. Another approach, focussed within this paper, is to directly utilize and extend functionalities provided by the AASs structure. This allows the AAS to manage itself. The access to the AAS is realized with the standard OPC-UA interface, including publish and subscribe functionalities that can be used to directly write data into the respective property value statement (PVS) of the AAS or to publish new values to the respective main units. The measurement, simulation and control unit serves as a combination of clients and servers in the OPC-UA communication. After a new device is positioned in the production system and the control system is informed, all robot operations are stopped, while the measurement unit is triggered, measuring the new physical configuration. New module IDs and positions are written directly into the AAS. The AAS itself works like a watchdog system, registering changes in the property set and publishing a change notification to the linked main units. From the start, all units subscribe to this topic. The notification contains information about the respective AAS. To receive the divergent values required for simulation, the simulation unit subscribes to the AAS' property topic deposited in the notification. After simulation, new robot paths are published to the data management, allowing an update of the module data set. After updating the robot paths, the AAS publishes a ready notification reactivating the robot control. The overall communication logic is shown in Fig. 4.

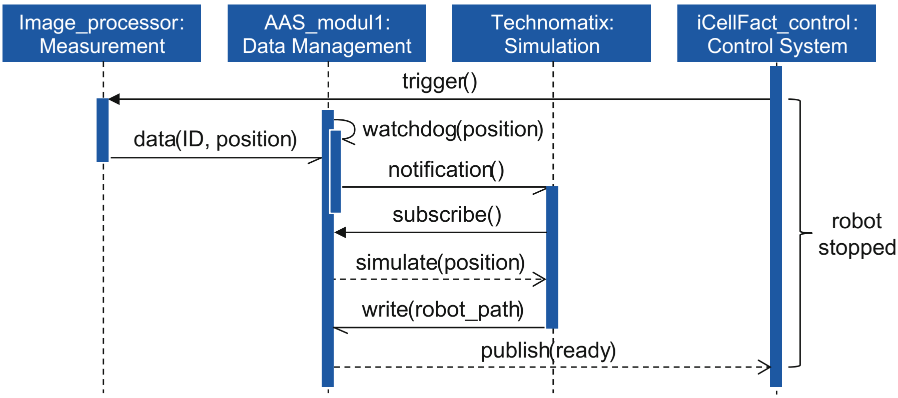

Fig. 4. UML sequence diagram for communication logic

Simulation and Control. The third architecture unit ‘simulation’ uses the position vectors deposited in the AAS to adapt the virtual system model. Based on the new model further robot path planning algorithms, collision detection and validation take place. After verifying the robot path by simulation, the path is written in the respective module AAS, making the path available for the overall control system. The ‘control system’ for all devices integrated in the production system reads necessary AAS properties and sets new states for the devices, e.g. verified robot paths can be extracted from the AAS and are sent to the robot controller for execution.

4 Exemplary Application

The image processing is evaluated in an exemplary application. First, the experimental setup is described followed by an evaluation of the current state of the measurement system.

Experimental Setup. The proposed concept for position detection of modules in a workspace using DMCs and image processing is evaluated within an experimental setup. The camera is attached to a six-axis robot mounted on a linear axis enabling flexible positioning. For a start, the camera is positioned 1.200 millimetres above a measurement field meeting the conditions in the mentioned cultivation platform for cell products. By positioning the camera’s optical axis perpendicular and centred on the field, defined measurement conditions are set. The measurement field itself includes multiple DMCs in different well-known positions and rotations. By manipulating the field’s height relatively to the camera, different z-positions are measurable. A monochrome camera with a 4.19 mega pixel sensor and a pixel size of 5.5 µm is used. The sensor’s global shutter reads all lines of the pixel sensor simultaneously. Thereby, possible image errors caused by vibrations are reduced. The camera lens has a focus length of 8 mm and an aperture of 1.4. The developed image processing algorithm is based on standard decoding algorithms for DMCs and the canny edge detector.

Evaluation. First, the deviations in x-, y- and z-direction are measured, taking into account different radial distances to the camera’s optical axis, see Fig. 5.

As shown in A, the absolute deviations of the measurement – in a distance of 1200 mm between the camera and the measurement field – in x- and y-direction are in the range of 0.28 to 7.69 mm, whereas the deviation in z-direction is between 36.02 and 51.13 mm. The results indicate an increase of the absolute deviation for the x, y and z position values with distance to the optical axis. This effect can be compensated by an improved correction of the image field curvature and distortion with polygons higher order. Still, there is a big gap between the deviations in x- and y-direction compared to z-direction. By calculating the magnification based on the code area, the precision and stability of the measurement can be enhanced compared to the measurement over the circle areas. In the diagrams B to D, the deviations in x-, y- and z-direction are plotted over the distance to the lens’ focal plane. The results in general show an increased deviation for x- and y-values with higher distances to the focal point. For z-positions, the deviation decreases.

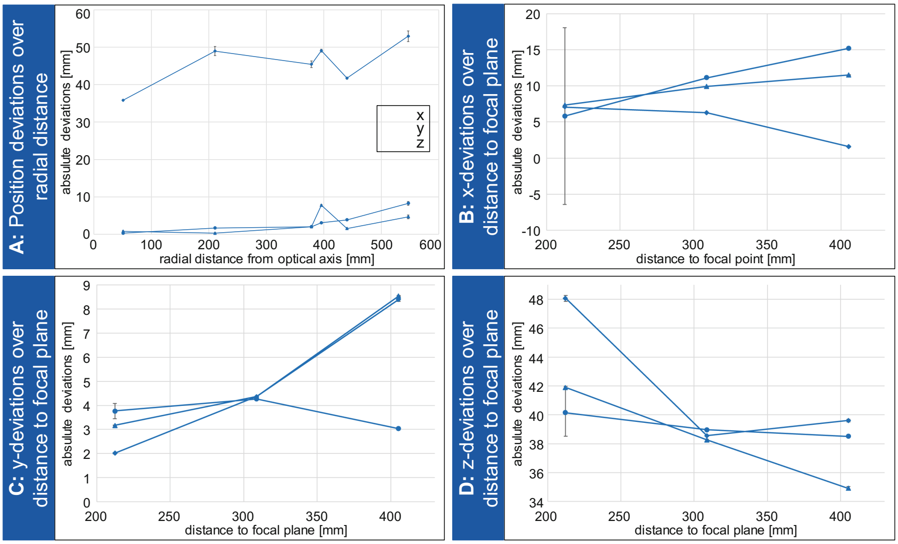

Fig. 5. Measurements of average position deviations in x-, y-, and z-direction

Secondly, the deviation of rotation angles around the z-axis are measured, shown in Fig. 6. The average absolute deviations for z-rotations of the DMCs over the radial distance to the optical axis are plotted in the left diagram. On average, the deviation for z-rotation in the focal plane is 0.59°. The distance from the optical axis has no significant influence on the measurement result. On the right side, the z-rotation deviations are plotted over the distance to the focal plane. The deviations increase with higher distances to the focal plane, still being in an acceptable range for robot operations. The scatter of the three plots can be explained by the codes' different radial distances to the optical axis.

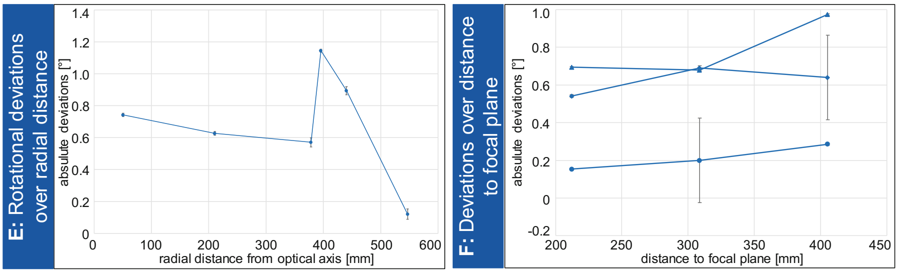

Fig. 6. Measurements of average deviations for z-rotations

5 Conclusion

In a first exemplary application, the presented concept for position and orientation measurement of plant modules based on modified DMCs has been explained and validated, showing its applicability and current limits for robot applications. The proposed data management enables a standardized and modular access to data from measurement, simulation, control and additional sources, allowing an adaption to available systems and tools. Thereby, the proposed architecture for robot programming allows an improvement of current approaches in terms of flexibility and transferability, being a first step towards autonomous reconfiguration of production systems. One major advantage is the easy integration in production systems and its usage even for non-expert operators. In the next steps, the data management has to be evaluated in detail and transferred to other automated production systems and the algorithm for image processing will be enhanced by different methods for image filtering and the superimposition of multiple images. Additionally, the usability of super resolution imaging for position detection has to be tested. Besides, a camera with higher resolution and a specified optic is tested in further steps.

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