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Procedia CIRP 86 (2019) 179–184

www.elsevier.com/locate/procedia

7th CIRP Global Web Conference
“Towards shifted production value stream patterns through inference of data, models, and technology”

The Assist-By-X system:

Calibration and application of a modular production equipment for visual assistance

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Abstract

Shorter production lifecycles, new challenges due to the advancing globalization, and increasing demand for individualized products are only some of the general conditions that internationally operating manufacturing companies have to face. Therefore, adaptable production systems are required which can be changed to the current requirements of the production process. In this article, a modular visual assistance system is presented which can be integrated in different production systems and environments. For a successful integration of the assistance system a calibration is indispensable, thus a calibration method for one component of the assistance system is discussed in detail. In order to control the system, a visual data flow programming tool is used in combination with MQTT as a standard communication protocol. By doing so, the programming effort of the system is reduced and new components can easily be added to the system by creating new flows.

Keywords: Modular Design; Adaptable Production Systems; Worker Assistance Systems

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1. Introduction

As a result of the progressive change from a supplier's to a buyer's market, the general conditions for industrial companies have changed dramatically. [1] In order to maintain competitiveness, products are increasingly diversified and individualized in ever shorter life cycles up to “lot size 1”. Furthermore, the fluctuating sales volumes caused by global competition lead to growing forecasting uncertainty, which increases the planning frequency. At the same time, products must be offered at ever lower prices, but with increasing quality requirements in mind. As the final step of the value chain, assembly is particularly affected by the above mentioned challenges. [2]

Consequently, efficient assembly must be accompanied by the necessary responsiveness and speed - adaptable assembly systems are required. At this, the modularity of the different components which are used in a production system is a key factor. [3] Modular engineering is an industry design approach that subdivides a large system into smaller versatile parts called modules. These modules are designed to be reused in any other adaptable production system with varying parameters. [4] Modular design also allows to react to changing requirements by quickly replacing unsuitable modules with modules with the required skills. Modular assembly systems are commonly

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10.1016/j.procir.2020.01.021

divided into process, basic, conveying, assistance and feeding modules. Each of the modules poses a specific ability and allows an interaction with other modules, the product and the operator. [5] The modules consist of the following parts: a Human-Machine Interface which allows operators to monitor the production and field devices that perform the commands e.g. from the Manufacturing Execution System (MES) using control units like Programmable Logic Controllers (PLC). A communication framework connects all the segments together and monitors the production process with higher control layers. [6] In this paper a modular production equipment for visual assistance is described which can be easily integrated in different production environments. The components of the module called “Assist-By-X” are controlled by a data flow application which is suitable for Industry 4.0.

2. Essentials

2.1. Modular Assembly Systems

A modular assembly system is the subdivision of the individual stations into basic, transport, assistance, feed and process modules. Each of these modules fulfills a certain functionality. In the following, each of the modules will be explained: The basic module is the foundation into which further modules or components can be integrated. The handling of the component from the material supply to the actual assembly process is carried out in feeding modules. In different cases, components are moved between the assembly processes with the aid of transport modules. The transport module represents the path on which the workpiece carrier can move from the current station to the next station. Assistance modules allow communication between worker and machine, support the worker during the assembly process or to operate the machine. The actual core task of assembly, joining, is performed by the process modules of an assembly system and thus represents the value-adding component. Additional devices are elements that are present in every assembly system but cannot be assigned to any of the aforementioned categories. [7]

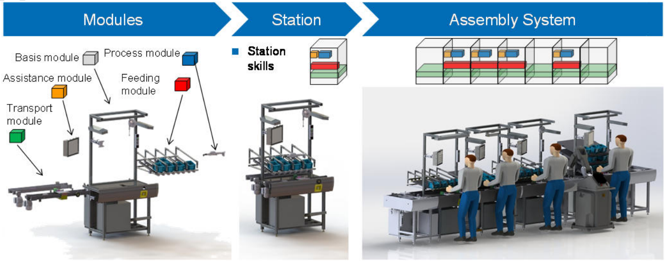


Fig. 1. Modular assembly system with four stations (following [8])

Fig. 1 illustrates a modular assembly system consisting of four stations that can be subdivided into the modules mentioned. For the planning of new or the adapting of existing assembly systems with their different stations, skill-based descriptions of the modules can help to find the optimal configuration for the current requirements of the products. From the product structure, assembly processes are derived that require certain skills for their execution. For example two parts that are joined with screws will need a process module that has the skill “screwing”, ideally this is further specified by the screw type and the necessary torque. Whereas other parts will need process modules with different skills, e.g. welding or riveting. Individual assembly processes and their required skills are summarized in skills sequences. Furthermore, modules are characterized by their specific skills. Afterwards, the assembly planer can use this as an assignment criterion to match the right modules to the processes and configure single stations up to the full assembly line in consideration of cycle times and line balancing. (see Fig. 1) [9]

2.2. Cyber-Physical Systems

In general, cyber-physical systems (CPS) are based on mechatronic systems, which represent a combination of technical objects, such as devices, buildings, production facilities, logistics components, etc., and embedded systems, sensors and actuators and human-machine. The main difference between mechatronic and cyber-physical systems can be found in the communication channel, since the Internet of Things (IoT) and Services is used instead of, for example, classic wired channels. This turns a passive object into an intelligent system that can interact with its environment. [10] In principle, CPS represent a connection between the virtual world and the real world or the physical object. The embedded systems form the intelligent unit of the CPS, since sensors and actuators are controlled by microcomputers and software and the actions and reactions are derived with the physical or virtual world. [11] The merge of several independent CPSs in the production environment creates a cyber-physical production system (CPPS) in which the CPSs pass on their own information to their environment (other CPPSs) or to other IT systems. [12] To create IoT scenarios within CPPS the use of different protocols, programming languages and Application-Programming-Interfaces (APIs) is necessary which can pose a complex task using traditional programming tools. Currently different programming environments are dealing with this problem. One approach is the modeling of complex data flows with the help of visual data flow programming languages such as Node-RED. It offers a web-based flow editor which can connect different hardware devices, APIs and online services. By the use of Node.js framework it is possible to take advantage of the JavaScript as well as event-driven models. [13]In addition to programming environments such as Node-Red, messaging protocols have also been developed for machine-to-machine communication (M2M) in order to provide efficient data flow, which is tailored to the requirements within IoT networks. One of the oldest of these protocols is the Message Queue Telemetry Transport (MQTT) protocol, designed specifically for lightweight M2M communication in constrained networks. MQTT is based on the publish/subscribe principle, in which messages are exchanged between different MQTT clients via a MQTT broker. Initially a MQTT client can publish messages with the help of a certain topic to an MQTT broker. One or more MQTT clients can subscribe to this topic from the MQTT broker. In this context, MQTT clients receive the messages for each topic they have subscribed to whenever new information is published. [14]

3. Assist-By-X

The Assist-By-X (ABX) system is one implementation of a modular assistance system combining the advantages of modular engineering as well as easily programmable cyber-physical systems communicating with their environment via MQTT. The idea for this project is to create a modular system that provides visual assistance for workers which can be adapted to different production environments with individual assistance tasks. In an assembly system it represents an assistance module, whereby the skills of the module can be defined by exchanging the projection device. For this reason, the system is called ABX, since the X is representative for the different devices that can be implemented. So far, a laser projector, a moving head spot and a smart video projector are implemented. Depending on the use-case it is expected to decrease processing times, probability of errors or create a safer working environment on the production line, thereby increasing worker performance. Existing commercial systems, such as “Light Guide Systems” by OPC Solutions, “Der Schlaue Klaus” by Optimum or “Human Interface Mate” by Arkite focus on using one projection system for the assistance task with commissioning and work processes aligned to the specific device. The ABX distinguishes from these systems as the requirements of assistance tasks are used as a basis. Suitable projection devices which offer the right skills to fulfill the task can be integrated into the system using a generalized work flow which is independent from the specific device.

3.1. Set-Up

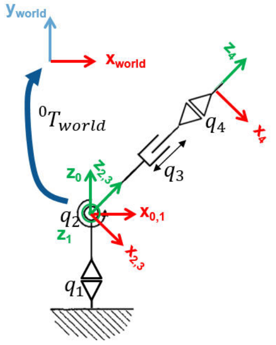
As a part of the whole assembly system, the set-up of the ABX is a component of the complete configuration respectively reconfiguration process of the assembly system. The ABX offers its skills for the assistance of the worker in the production process, whereby the skills of the ABX results as a whole of all skills of the available individual components. As a result, there are overlaps in the skills of the components; for example, the projection of a point is possible by a projection of a laser, a video projector as well as a moving head spot. In this case, the planer of the assembly system has to make a decision which component is most suitable for the specific task. On the other hand, there are unique skills that a component can offer, e.g. the projection of paths over larger distances can be realized by a moving head not by the other projection systems.

After the planning of the assembly system with the appropriate configuration of the ABX, different processes for hardware and software are necessary to integrate the module into the assembly station. Various data interfaces like Ethernet, DMX or HDMI are possible according to the projection device. Just by themselves, the projection devices are not able to communicate with their environments. This is why the projection devices have to be combined additional “intelligent” components like microcontrollers (e.g. Raspberry Pi), computers or PLCs which allow the communication with the MQTT broker and thereby enabling modularity. In the next step some basic software settings have to be adjusted, e.g. defining IP-addresses and MQTT topics, when the device works in the environment for the first time. After that, a calibration for the projection device has to be performed in order to operate correctly to the different production environments. Eventually the ABX should work in an assembly station in a network of modules supporting assembly processes that are normally controlled by a higher-level IT-system. Therefore, the commands are initially sent by this IT-system with help of an MQTT topic to the MQTT broker, from where the implemented device can get the message by subscribing to the topic. Any device-specific controller is able to decode messages and convert it to specific functions of that device, so that whenever the requirements of the production process change, the IT-system will send commands to the ABX and change its behavior.

As mentioned before, different projection devices can be used in the system. Controlled by an industrial PLC the laser projector generates visible laser lines on the work surface or the assembly object based on 2D shapes or CAD data. Thereby, worker assistance, e.g. for alignment and positioning of components, can be realized on parts with a complex shape. In contrast, the video projector works with image or video files to provide the work space with instructions and has to be controlled by a microcontroller or PC. In the next chapters the crucial process steps of the commissioning and operation of the ABX system will be explained in detail. To not exceed the frame of this paper, the focus is placed on the ABX configuration with the moving head spot as the projection device. This has the following reasons: The moving head is a device usually used as theatre and event technology and consequently does not have a standard calibration method which can be executed by a production worker rather than a light technician. Moreover, the moving head is not a cyber-physical-system and cannot communicate with its environment, whereby it has to be equipped with a Raspberry Pi to meet the demands of an IoT scenario. The processing of the MQTT message into the device-specific commands is realized with the help of a Node-RED flow and is carried out with the other devices in a comparable way.

3.2. Calibration

The moving head has an open serial kinematic. Therefore the kinematic and modelling problem of the moving head can be solved analogous to an articulated robot. Then, the moving head kinematic is modelled by using the Denavit-Hartenberg convention. [15] Each joint of the kinematic is modelled by a coordinate system. Where $\delta_{i,i-1}$ and $d_{i,i-1}$ denote respectively a rotation and translation about $\underline{z}_{i-1}$ axis. Furthermore, $\lambda_{i,i-1}$ and $l_{i,i-1}$ represent respectively a rotation and translation about $\underline{x}_i$ axis. The first two joints are revolute active joints, where the third one is prismatic. The third joint is adjusted passively. The so-called iris value can adjust the scale of the projected area and serves as a value of the third joint. (see Fig. 2) The fourth joint is an active revolute joint and serves to set the orientation of the projected area. This parameter is less important for the calibration and would not be considered in the frame of this work. The coordinate system of the moving head is located on the intersection of the first and second axis and the z axis it located along the first rotation axis. The x axis results from the cross product of the first and the second axis. The aim of the calibration is to identify the transformation matrix ${}^{0}T_{world}$ between the moving head and the world coordinate system. A methodology is developed at ZeMA for this purpose (see Fig. 3). Four points are defined on the world coordinate system. The points P$_1$ and P$_2$ are laying on the x axis of the world coordinate system while P$_4$ lies on the y axis and P$_3$ lies on the origin. The distances between the points are known.



Link	$\delta_{i,i-1}$ [rad]	$d_{i,i-1}$ [m]	$l_{,i-1}$ [m]	$\lambda_{i,i-1}$ [rad]
1	q_1	0	0	$\frac{\pi}{2}$
2	q_2	0	0	$-\frac{\pi}{2}$
3	0	q_3	0	0

Fig. 2. Modelling of the moving head kinematic with the help of Denavit-Hartenberg convention. [15]

A connection line defines the chordal distance between the origin of the moving head coordinate system and one point. The length of the connection lines is unknown. The angle between two connection lines is the angle of the rotation matrix that transforms the moving head from one configuration to another. The rotation matrix is dependent on the angles of the first two joints. These are measured by increment sensors. The lengths of the connection lines are determined using the developed methodology.

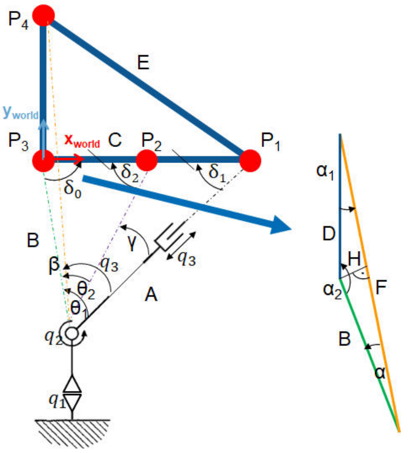


Fig. 3. Calibration of the moving head.

Let c_1 and c_2 be two constants derived considering the sine law:

$$c_1 = \frac{B}{sin(\delta_1)} = \frac{C}{sin(\theta_1)} \qquad (1)$$

$$c_2 = \frac{B}{sin(\delta_2)} = \frac{C/2}{sin(\theta_2)} = \frac{A_2}{sin(\delta_3)} \qquad (2)$$

The angle θ is defined as:

$$\theta = \theta_2 - \theta_1 \qquad (3)$$

The following equality can be derived by considering the angle δ_0:

$$\delta_0 = \pi - \theta_2 - \delta_2 = \pi - \theta_1 - \delta_1 \qquad (4)$$

$$\Rightarrow \quad \theta_2 + \delta_2 = \theta_1 + \delta_1 \qquad (5)$$

$$\Rightarrow \quad \delta_1 = \delta_2 + \theta_2 - \theta_1 \qquad (6)$$

Therefore, the angle δ_1 can be expressed as:

$$\delta_1 = \theta + \delta_2 \qquad (7)$$

Substituting (7) in (1):

$$B = c_1 \cdot sin(\delta_1) = c_1 \cdot sin(\theta + \delta_2) = c_2 \cdot sin(\delta_2) \qquad (8)$$

Using the trigonometric formula:

$$c_1 \cdot sin(\theta + \delta_2) = c_1 \cdot sin(\theta)\, cos(\delta_2) + c_1 \cdot cos(\theta)\, sin(\delta_2) \qquad (9)$$

$$\Rightarrow \quad c_2 \cdot \sin(\delta_2) = c_1 \cdot \sin(\theta)\cos(\delta_2) + c_1 \cdot \cos(\theta)\sin(\delta_2) \qquad (10)$$

$$\Rightarrow \quad (c_2 - c_1 \cdot cos(\theta)) \cdot sin(\delta_2) = c_1 \cdot sin(\theta)\, cos(\delta_2) \qquad (11)$$

$$\Rightarrow \quad \delta_2 = arctan\left(\frac{c_1 \cdot sin(\theta)}{c_2 - c_1 \cdot cos(\theta)}\right) \qquad (12)$$

Due the geometrical constrains, the angle δ_2 is limited between 0° and 180. The length B is then determined as:

$$B = c_2 \cdot sin(\delta_2) \qquad (13)$$

The angle δ_3 is defined as:

$$\delta_3 = 180 - \delta_2 - \theta_2 \qquad (14)$$

The length A is then determined as:

$$A = \sqrt{B^2 + C^2 - 2BC \cdot cos(\delta_3)} \qquad (15)$$

Applying the sine law on the upper triangle:

$$\frac{F}{sin(\alpha_2)} = \frac{D}{sin(\alpha)} = c_3 \qquad (16)$$

$$F = c_3 \cdot sin(\delta_3) \qquad (17)$$

The position of each P$_1$, P$_3$ and P$_4$ with respect to the moving head coordinate system is calculated after determining the lengths A, B and F. Due to the inaccuracies in the system, P$_3$ is assumed to lie on the x axis of the world coordinated system and deviate with small error from its origin. *P_1 and P_4* lie on the x and y axis of the world coordinate system respectively. The z axis of the world coordinate system ${}^{0}\underline{z}_{world}$ with respect to moving head coordinate system is the normalized crossproduct of the vectors ${}^{0}\underline{r}_{P_1,P_3}$ and ${}^{0}\underline{r}_{P_4,P_3}$. The x axis ${}^{0}\underline{x}_{world}$ is then defined as a normalized vector of ${}^{0}\underline{r}_{P_1,P_3}$.The y axis ${}^{0}\underline{y}_{world}$ is defined as a crossproduct between the z and x axis. The Origin of the world coordinate system with respect to the moving head coordinate system ${}^{0}\underline{r}_{O_{world,O_0}}$ then is the intersection between the line passing through P_1 along ${}^{0}\underline{r}_{P_1,P_3}$ and a line passing through P_4 along ${}^{0}\underline{r}_{P_4,P_3}$. The transformation matrix ${}^{0}T_{world}$ then is:

$$ {}^{0}T_{world} = \begin{pmatrix} {}^{0}\underline{x}_{world} & {}^{0}\underline{y}_{world} & {}^{0}\underline{z}_{world} & {}^{0}\underline{r}_{O_{world,O_0}} \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (18) $$

After calibration of the moving head the latter is able to project any position in its working space. The coordinates of the projected position $P_p = \left({}^{0}x_p,\ {}^{0}y_p,\ {}^{0}z_p \right)^T$ is send to the controller of the moving head via MQTT. The desired configuration of the moving head is determined by solving the inverse kinematic problem of the kinematic model. Note that there are four mathematical solutions for a given position, but only two of the solutions are practically possible. Here one of these solutions is described. The second solution is derivate by subtracting the angle value from 360°.

$$ q_1 = arctan2\left({}^{0}x_p,\ {}^{0}y_p \right) \qquad (19) $$

$$ q_2 = arctan2\left(z_p,\ \sqrt{z_p^2 + \sqrt{{}^{0}x_p{}^{2} + {}^{0}y_p{}^{2}}} \right) \qquad (20) $$

The value of the third joint is adjusted by the iris value, if possible.

$$ IRIS = \frac{\sqrt{{}^{0}x_p{}^{2} + {}^{0}y_p{}^{2} + {}^{0}z_p{}^{2}}}{K} \qquad (21) $$

Where the factor K is determined during the calibration process. It is defined as the mean values of the quotients of the determined length and adjusted IRIS. During the calibration the IRIS is adjusted manually so that the project circle at the four points has the same radius.

3.3. Controlling the moving head spot with Node-RED flows

In order to integrate the moving head in the production environment it was necessary to develop a Node-RED flow that runs on Raspberry Pi, receive a certain signal through the MQTT protocol and then in response to that change the DMX channels of the device accordingly. The majority of stage lighting devices are now operated using the DMX512 (or just DMX) standard protocol for communication. The DMX has a tree-like structure: there are universes, which represent different DMX networks; each universe contains up to 512 channels, with each device usually taking up 13 channels; each channel has a range value from 0 to 255, which allows to control the device. For the most use-cases in production the moving head needs to perform movement in two directions, change the light colour and intensity, strobe effects and adjust the size of the projection depending on how far the surface of the projection is. For this reason, the scope of the application was reduced to these channels. Since channels often do not align when using different moving heads and the developed flow should work independently from the actual hardware, a set-up file is needed which defines the assignment of the channels to the functions. The calibration file contains the information derived from the calibration process described in chapter 3.2. The results of the calibration are then used as a basic framework for calculating necessary pan and tilt of the moving head light to project at any other point on the projection space. After the MQTT node receives the point coordinate as an array [x, y, z], it is processed by the Python calibration code to get the proper values required for the moving head. In combination with a node that interprets the set-up file, the values are then separated into different channels and sent to their specific function node, which converts them into the appropriate message format for the DMX Ethernet Node.

4. Use-Cases

4.1. Picking assistance

In the first use-case a typical picking assistance task of manual assembly processes is realized by the ABX, demonstrating the overlapping skills of two devices: the laser projector and the moving head. Manual assembly processes in multi-variant production lines can be secured by visual assistance and help to increase product quality. The work space is described in the following: On the workbench, there are multiple carrier boxes with different parts in them. The carriers can be placed in any desirable position. On the corner of the carriers Augmented Reality (AR) markers are placed. Each marker contains a part ID that corresponds to the ID of the same part in the MES, which controls the production process. In addition to the projection devices, there is a depth camera mounted over the work space. The camera is closed system which is able to communicate via MQTT. Using the AR markers, the locations of all carriers on the workbench are detected by the camera and recorded with the corresponding marker ID. Depending on the process step, the MES sends the ID of the component to be assembled to the camera system. This information is used to identify the carrier with the correct marker ID. The corresponding coordinates are then sent from the camera to the ABX using MQTT. The message contains in itself only the coordinates of the carrier. Depending on which projection system is used at the given moment, the process will diverge from this point. The laser projection system projects a line between two points on a white stripe at the top of the box to highlight the carrier with the needed parts. The moving head, on the other hand, projects a light beam at the middle of box (see Fig. 4). To enable a flexible work space, the camera updates the coordinates of the carriers in a defined time interval, so that the worker can to rearrange the carrier boxes during the process.

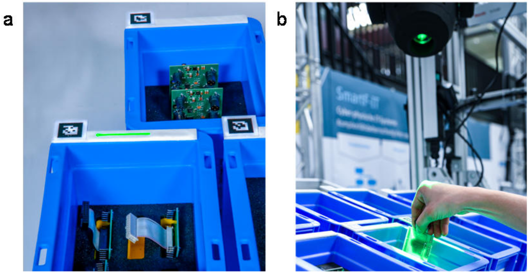


Fig. 4. Picking assistance with (a) laser; (b) moving head projection.

4.2. Work-space projection in human-robot-collaboration

Another use-case is the visual assistance of human-robot-cooperation in which humans and robots work together in a shared workspace. The acceptance of the worker in these new work situations is an essential factor for the success and effectiveness of the production system. Therefore, it is important to intuitively indicate the human in which system state the robot currently is and to visualize alterations of the system state. In the built up demonstrator the ABX system is used for displaying the individual workspaces of human and robot, as shown in Fig. 5. In the assembly line a robot is mounted on a 7th axis and can be moved along the line carrying out assembly processes at predefined different places. In this scenario two projection systems are needed in order to fulfil the assistance task. Through the modular design this can easily be realized by either adding an additional MQTT topic and assign each topic to a moving head or by extending the MQTT message by an integer that defines which moving head should move. For this case, the message containing the coordinates was extended by a value n (number of the moving head) so that the array [x, y, z, n] contains all necessary information. The upper control layer is the PLC of the robot which sends out MQTT messages when the robot is moving to another position which triggers the adjustment of the moving head spot(s).

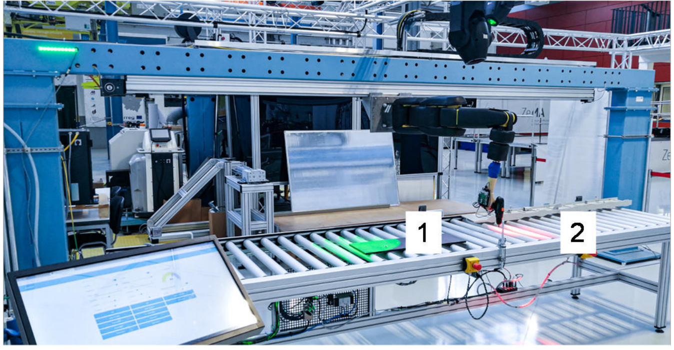


Fig. 5. Two moving head spots displaying work-spaces of human (green, 1) and robot (red, 2) in an assembly line

5. Conclusion & Outlook

A modular production equipment for visual assistance, called Assist-By-X, has been introduced which can be used within skill-based planning processes of assembly systems. With the simple implementation of different projection devices with the help of MQTT and Node-RED programming effort is reduced while the possible application range is increased, whereby the application in different production environments is ensured. In addition to that, it was shown that with the combination of technologies, like the Raspberry Pi, a mathematical modelling and calibration and IoT communication protocols it is possible to adapt devices from other industries to the requirements of modern production.

The focus of future work will be adding more skills for the already usable devices. At the moment the focus of the ABX was to enable all devices to realize a point projection as a basic feature. A possible extension, e.g. for the moving head, could be path projections which could be used to indicate the path of automated guided vehicles or show the way to the logistics staff to the material that needs to be picked up. Another future target is implementing new devices that complement the skill-set of the ABX.

6. Acknowledgement

This paper was written in the framework of the research project KomZetSaar, which is funded by the BMWi - Federal Ministry for Economic Affairs and Energy and supervised by the lead partner DLR- German Aerospace Centre.

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