

SYSTEM IDENTIFICATION OF ASSEMBLY CELLS – INCREASED ACCURACY AND DEMAND-DRIVEN RECONFIGURATION

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Abstract: Today's industrial assembly systems have to enable individualized production as well as featuring a high degree of automation to cope with both quality requirements and increasing cost pressure. One approach in engineering flexible assembly cells is to use co-operating robots. In order to automate small series economically, these assembly systems are programmed offline. To avoid extensive online correction and resulting long downtimes, discrepancies between the simulation model and the real cell have to be minimized. Therefore, the kinematic parameters of the assembly system are to be identified. The whole system will be broken down to basic subsystems whose properties are determined by measurement. The relevant parameters can be calculated from these measurements and subsequently used with offline programming methods.

Key words: assembly, tolerance concept, robotics, reconfiguration.

1. PROBLEM DESCRIPTION

There has been a fundamental change in the conditions governing manufacturing industry in recent years. Progressive globalization, rapid technological development and changes in the resources situation are responsible for increasing complexity and dynamics in industry and the industrial environment. One of the consequences is a further reduction of product life cycles, a sustained increase in the number of versions of products and constant pressure to cut manufacturing costs. Assembly systems and processes are particularly exposed to these pressures, as they add a large part of the value in the manufacturing process. Manufacturers in high-wage countries additionally face the need to decrease wage costs by enhancing automation.

The goals of individualized production in connection with a high degree of automation lead to conflicts. One approach is to use flexible assembly systems that can be configured appropriately to the demand of the process.

2. RECONFIGURABILITY

The required flexibility for automated assembling of varying products is mostly achieved by robotic systems. Adequate assembly cells can be particularly realized through the use of co-operating robots. These robots can be set up for different tasks by retooling and reprogramming. Besides the operating of assembly tools, handling tasks are feasible with the help of grippers.

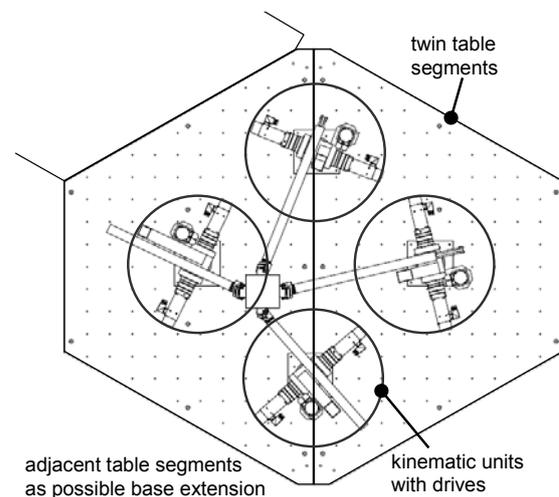


Fig. 1. Reconfigurable assembly cell.

In case of small series with a high number of product variants, offered flexibility may not be enough. Such assembly systems have to provide the ability to be configured appropriately to the demands of switching tasks. But the working space of common stationary robots is kinematically restricted. To resolve these limitations, smaller lightweight robots with easily reconfigurable positions can be used. In addition to the flexibility achieved through retooling or changing the gripping points, the lightweight models can be repositioned (Figs. 1 and 2). According to the task, the assembly cell can be reconfigured driven by the content demand of the user [1].

Due to reconfigurability, not only new opportunities arise. They are accompanied by new demands on the control and programming of such assembly systems. Whereas assembly personnel can adapt to the new tasks independently, handling devices and industrial robots have to be reprogrammed. The movements of all co-operating devices within the assembly cell have to be coor-

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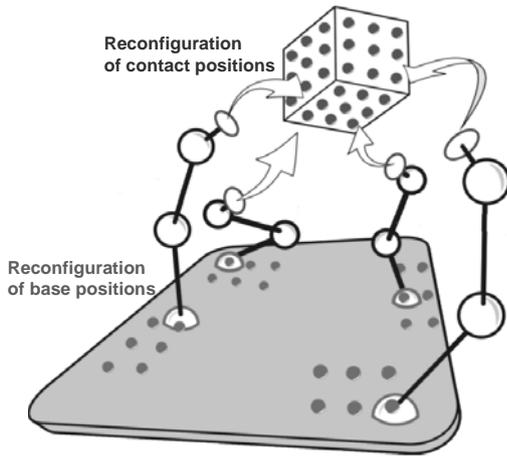


Fig. 2. Potential adaptations of the configuration.

dinated, which results in significant additional expenses in comparison to stationary robot systems. But in order to automate small series economically, task switching may not result in long downtimes.

Common ways of programming robots are “online” methods like “Teaching” or “Playback”. Both approaches necessitate programming operations directly inside the assembly cell that lead to long downtimes so that they are not suitable for frequently changing tasks.

An alternative and more time efficient method is “Offline Programming” which can be executed parallel to the still ongoing work task. It enables generating a robot program without using the real machine. Programming takes place in a simulation environment and the results are subsequently transferred to the robot control. This procedure requires the modeling of both the robot kinematic and the whole assembly system including assembly equipment. The models are mainly based on the CAD data of the cell components.

A big disadvantage of this programming method is the possible deviation between offline generated movements and the real movements of the robot. Due to this, additional time-consuming online programming is often necessary to adapt the programs to the cell. A direct transfer of the programs usually implicates limitations, because cell-models used for calculations are incorrect. With the help of an integrated system identification, it is possible to identify the optimum model parameters of the assembly system and thus to reduce the gap between simulation and reality.

3. SYSTEM IDENTIFICATION

Therefore, an approach was developed to enable identifying the parameters of an assembly system and to provide them for offline programming and controlling. The following diagram illustrates the basic sequence of system identification (Fig. 3).

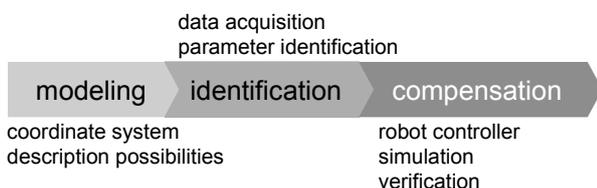


Fig. 3. Approach to system identification.

In the first step, a nominal model of the assembly system is created. For analysis and identification the system is decomposed into subsystems. The parameters of each subsystem are identified by use of established methods. By means of internal and external measurement systems, the necessary data for calculating the model and describing the characteristic parameters is collected. This step is followed by an adjustment of the control and the simulation environment. Finally, further measurements are carried out to verify the identified model.

3.1. Modeling of assembly systems and resulting deviations

The first step of the procedure is to model the assembly cell with a parametric model. Based on the CAD data, the models are created in the graphical simulation environment. Besides handling devices, assembly equipment and the product, a complete model contains all additional equipment (fences, machinery casings, etc.) to enable the use of a body conflict tool. Then all objects within the cell are provided with coordinate systems. It is important to define the coordinate systems in a way that makes them identifiable afterwards. Appropriate positions are body edges or axes of rotation, as they can be touched with an external measurement system. To describe the coordinate systems relatively to each other, a fixed world coordinate system is defined.

The robots are described by means of DH parameters. This model description formulated by Denavit and Hartenberg allows describing manipulators with only four parameters per joint [2]. It is the most widespread description method for industrial robots.

Figure 4 shows an example of an assembly process. A robot with a gripper places an optical component on a base plate. The base plate is fixed on a workpiece carrier at the installation surface.

To program such a process offline, the relative positions of robot and assembly equipment and the location of the base plate on the installation surface have to be determined in advance. For the positioning of the optical component the accuracy of the robot is important. Only if the component can be supplied in the required quality, the assembly process is executable. These influences can be represented in the tolerance chain (Fig. 5).

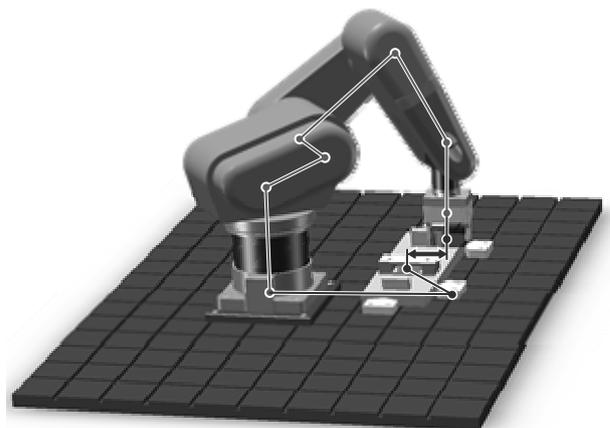


Fig. 4. Assembly Process: joining of optical components.

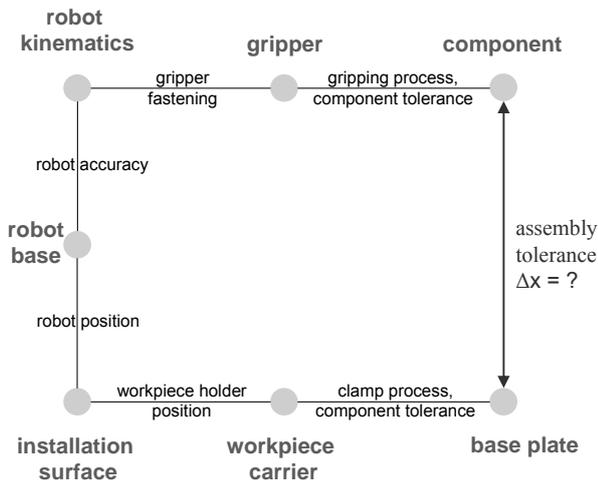


Fig. 5. Modeling of the process with the help of tolerance chain analysis.

Due to the lack of information about the critical relations, this process had to be programmed online without system identification. Relations could only be determined based on the CAD data, but in this case tolerances of the individual components would lead to a large position error. Several reference measurements show that the position error mainly includes the positioning accuracy of the robot and a constant offset.

There are several reasons for the differences between simulation and reality. Systematic errors, which can be reproduced properly in a model, have to be distinguished from stochastic effects that are not modeled. In practice, however, some systematic effects are ignored to restrict the complexity of the model (Fig. 6). The more accurate the description, the more parameters are needed to describe the model. Accordingly, the costs for the determination of all parameters increase. Therefore, the chosen model has to contain all relevant effects and to neglect the terms that are not relevant.

Prior to the parameter identification it has to be determined which of all parameters are relevant for programming. Therefore, the assembly process is modeled and analyzed to identify the influences of the assembly equipment. Visualizing tolerance chains of the process enables breaking down the entire system into subsystems so that every chain link represents a subsystem interface. The consideration includes both the component tolerances caused by manufacturing and the assembly tolerances.

With the help of the developed method it is possible to identify the real parameters of the system and hence to minimize the position error Δx (Fig. 5).

3.2. Identification procedure

Although the description for robots with DH parameters is kinematically complete, not all parameters can be identified independently. However, the identifiable model may not contain uninfluential or redundant parameters. Otherwise, the equation system would not be solvable uniquely. In order to reduce the position error between the model and the real system anyway, it is necessary to use a non-redundant model for the parameter identification.

The model reduction can be achieved by imposing a Jacobian. The Jacobian shows the influence of parameters on the position error. From the partial derivatives, fundamental relations regarding the impact of parameter changes on the position error can be determined. The Jacobian can contain linear dependent columns, so that individual parameters are only identified jointly. This is the case if two successive axes of rotation of a robot, $i-1_z$ and i_z , are parallel to each other (see Fig. 7). The resulting matrix is singular, because the columns of the axis length coefficients Δd_i and Δd_{i+1} are equal in this case.

This linear dependence has the consequence that only the sum of the axes lengths d_i and d_{i+1} has to meet a certain value that can be arbitrarily apportioned to the two lengths. Practically, this means that determining the sum of the lengths enables the creation of a regular system of equations by fixing one of the parameters.

After a non-redundant model was created, the next step is to identify the parameters. In this approach for system identification, there is a necessary distinction between the initial identification and the identification after reconfiguration. In the course of the initial identification, all parameters of the system have to be identified, whereas after the reconfiguration only the changed parameters are left to be identified. This minimizes the measurement effort and allows a faster restart of the assembly.

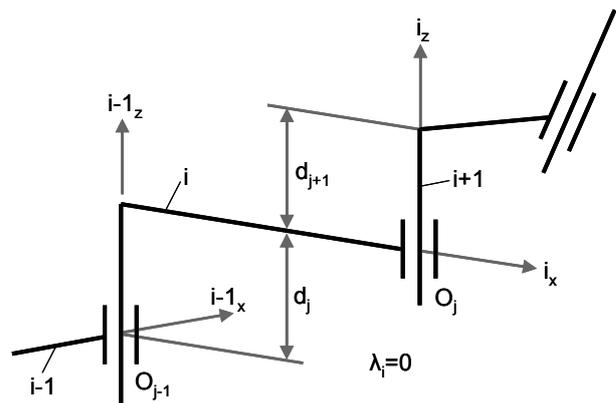


Fig. 7. Crossing angle $\lambda_i = 0$.

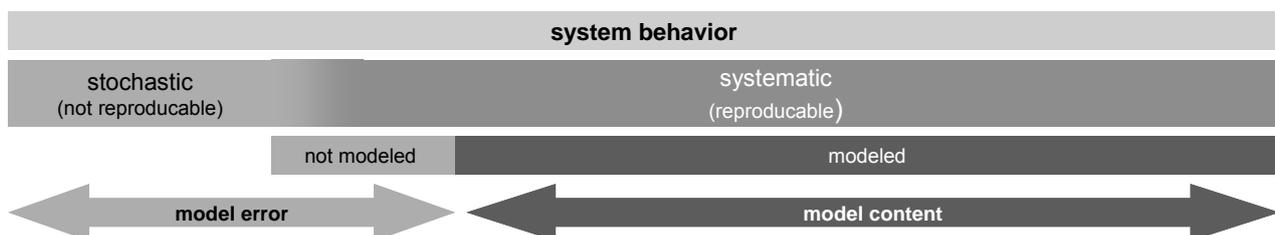


Fig. 6. Model content [3].

For both methods, a suitable measurement system is transformed into world coordinates of the assembly cell. Therefore, the previously defined characteristics of the world coordinate system are measured. The coordinate system can, for example, be generated by the intersection of three planes. It is important that this coordinate system can be identified reproducibly, so that not all resources need to be re-calibrated after the reconfiguration.

At the initial identification of the system all collision bodies within the workspace are uniquely identified to adjust the collision model. Therefore, as for the world coordinate system, various characteristics are measured to determine the location and orientation of the body coordinate system.

Subsequently, the manipulators are measured according to the state of the art. Corresponding methods are, for example, described in [4, 5, and 6]. A common procedure is the numerical identification of the entire system. For this, several points spatially spread within the working space are recorded with an external measurement system. By comparing the calculated values with the actually measured values, an error function can be established. With the help of the Gaussian method of nonlinear least-squares problems, the model parameters were altered until the position error has fallen below a defined threshold. The return value of the optimization is a model that describes the real robot system (Fig. 8).

Normally, the parameters of a robot will not change during the reconfiguration. It is hence sufficient to identify only the robot base coordinate system after reconfiguration (Fig. 9). To determine the robot base, a simpler method can be used. For the identification a reference movement is executed, which is covered with an external measurement system.

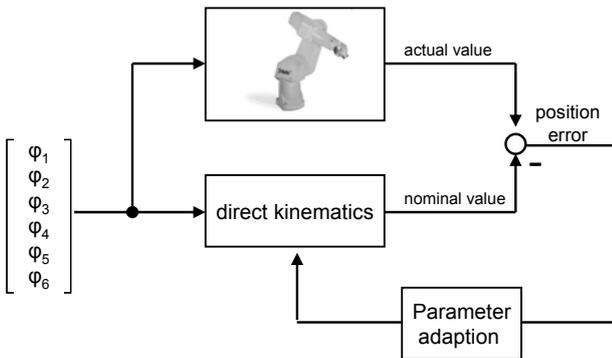


Fig. 8. Parameter identification of a robot.

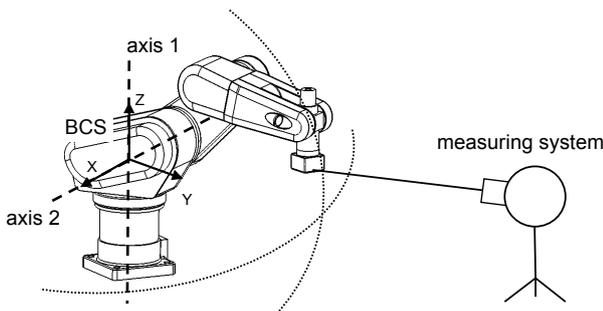


Fig. 9. Identification of the robot base coordinate system.

The Z-axis of the coordinate system is always the first axis of the robot and the origin on the Z-axis of the robot base coordinate system is specified by the manufacturer.

For jointed-arm robots, the base coordinate system is located either at the intersection of the first and second robot axis or at the intersection of the first axis with the normal between the first and second axis. To identify the first axis, the circular movement of the axis is measured at the tool center point (TCP). The rotary motion results in a circular path. The normal to the center of the circle corresponds with the first axis of rotation. Afterwards, this procedure is executed for the second axis to determine the second condition for the origin of the coordinate system. To determine the XY plane of the coordinate system, the measured circular area of the first axis is moved to the origin. The second circle can be used for the orientation of the coordinate system, because in most cases the first and second axes are perpendicular to each other.

3.3. Compensation and verification

The last steps of the identification process are compensation and verification. To make the identified models usable, it is important to adjust both the robot controller and the simulation environment. Particularly during the adaptation of the robot control, problems can arise because not all parameters can be changed by the user. That is, for example, due to the fact that the implemented inverse kinematics is based on simplifications such as all angles are assumed to be exactly 0° or 90°. If the model differs from these values, the stored inverse kinematics can not longer be used and another way to adapt the controller has to be found. This can be achieved by an algorithm for specifying Cartesian coordinates. The target coordinates from the path planning are converted into joint coordinates with the calibrated inverse kinematics. Afterwards, the joint coordinates are converted back into manipulated Cartesian coordinates with nominal direct kinematics. Using the implemented inverse kinematics and the real kinematics, the robot reaches the target coordinates (Fig. 10).

In addition to the robot controller, the simulation cell is also to be adjusted. The equipment is moved and oriented according to the real cell.

Once the models were adjusted in the simulation and the controller, it was necessary to validate the result. Especially when the model has been generated numerically, this step is essential, as that model may be correct for the measured points, but does not apply to the whole working area of the robot. In the other target points on the working area struck distributed and measured, the model can be verified.

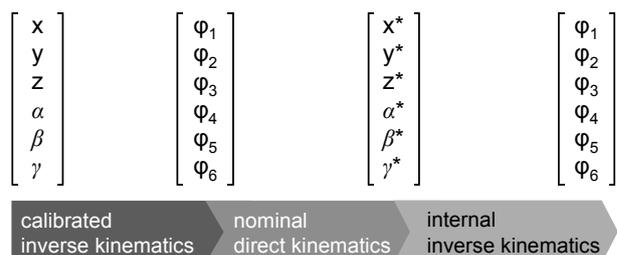


Fig. 10. Algorithm for selecting Cartesian coordinates.

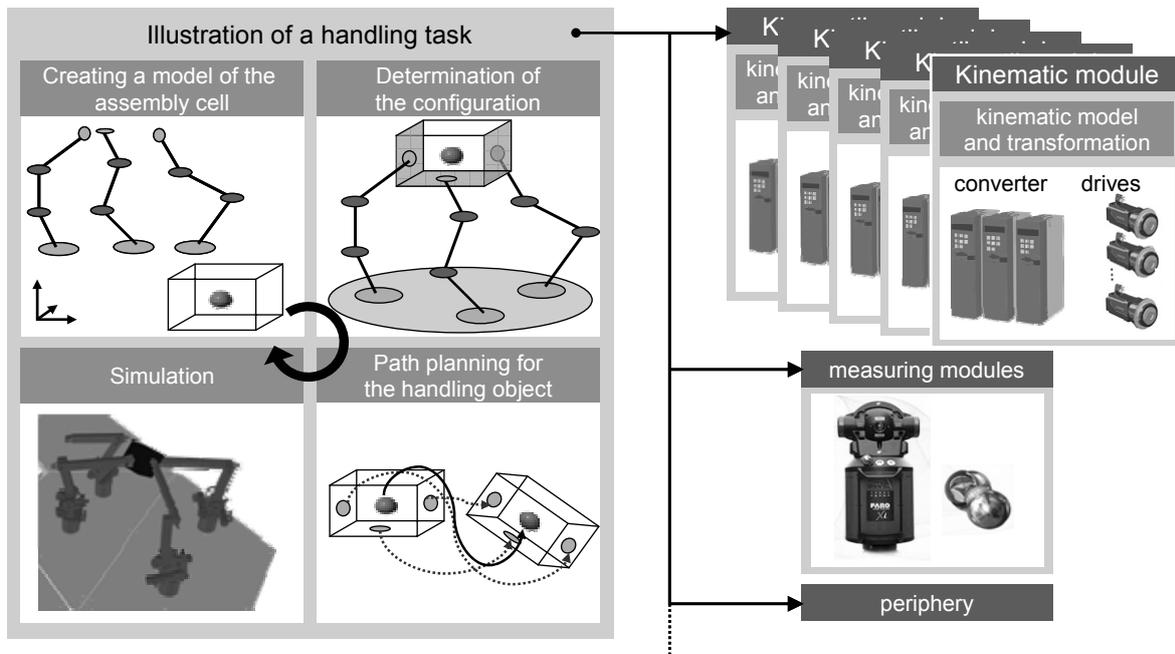


Fig. 11 Control and programming approach for reconfigurable assembly systems.

4. APPLICATION

The Chair of Assembly Systems is highly involved in the research of reconfigurability and system identification and has therefore developed a dedicated demonstrator. This new handling system provides more degrees of reconfigurability than a conventional handling system. This fact has to be considered in the control concept for the assembly platform. As the number and position of the arms can be theoretically varied for each handling task, the current system configuration has to be identified and considered for the control of each arm. The approach developed at the Chair of Assembly Systems divides the handling system in kinematic modules (Fig. 11).

Starting point of the following implementation is the motion path of the handling object, which is given by the user or the handling task. The path planning is executed within a simulation software, in which the assembly cell is modelled. On the basis of the object trajectory a suitable system configuration can be calculated, checked concerning reachability and collisions and modified when needed. The trajectory of each kinematic unit is derived indirectly from the trajectory of the handling object. This way of describing a handling task is initially independent of the type and number of handling units and therefore appropriate for programming the modular, reconfigurable assembly platform. To generate the trajectory of each kinematic unit, several gripping points are defined on the surface of the workpiece. The transformation of the object basis to each gripping point is considered constant during the motion and the resultant trajectory describes the movement of the TCP of each arm. In a final step the TCP-trajectory is transformed to the motion control of the servo drives by the inverse kinematic of each module.

5. SYSTEM OPTIMIZATION

With the help of the system identification, the individual tolerance chain links can be shortened by identify-

ing the real values metrologically and without using the manufacturing and assembly tolerances. But accuracy can even be enhanced during the ongoing process using system identification.

For the example shown in chapter 3, an additional vision system enables determining the position of the optical component inside the gripper after each gripping process. The location of the base plate could also be inspected before positioning the component and hence be included in the path planning. So during the process the terms for part and assembly tolerances are replaced by one term containing only the measurement uncertainty (Fig. 12).

In some cases, the accuracy of the system may not be enough and the process can not be realized within the required accuracy. Beyond the system identification, there are still other ways to achieve a further optimization of the system.

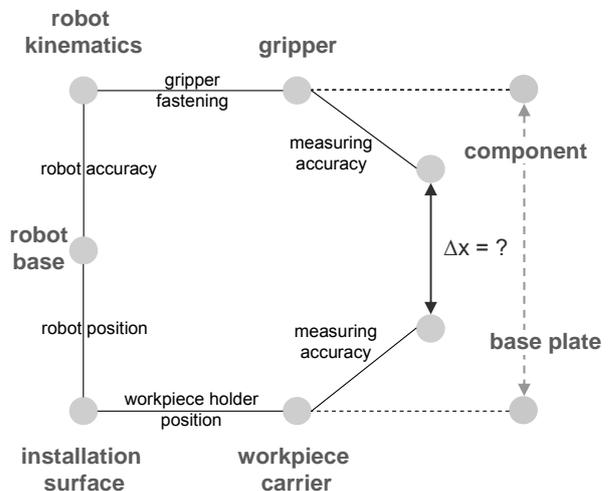


Fig. 12. System optimization by changing the tolerance chains.

