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Adapted task configuration of a reconfigurable binary parallel robot with PRRRP structure

Daniel Schütz*, Annika Raatz and Jürgen Hesselbach

Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Germany

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SUMMARY

Binary-actuated robots offer a discrete workspace with the advantage that no feedback control is needed, as their actuators have two mechanical end-positions. This contribution focuses on a planar parallel robot with a PRRRP structure and driven by rodless pneumatic cylinders. Thus, the robot's workspace only features four destination points, which can be reached quickly and with high repeatability. Because of the fact that there is no possibility to reach in discrete points, an adapted task configuration is essential. The objective of this work is to establish and validate a synthesis and calibration technique for binary parallel robots with a PRRRP structure.

KEYWORDS: Parallel manipulators; Modular robots; Manufacturing; Automation; Design; Binary robot.

1. Introduction

Industrial robots are the best choice to accomplish fast and precise handling tasks in factories. In addition, robots are very flexible, as the control programs can be easily changed for new applications. Within this broad range of factory tasks are a large set of tasks that only require a few destination points to be reached. Moreover, these points seldom change their coordinates. This means that conventional robotic systems with continuous actuators and an extensive feedback control are able to accomplish these tasks but they are often overdone, and are thus not cost-effective. To reduce the initial investment costs of robots, Chirikjian[1] presents a new paradigm in robotics based on binary actuations. The advantage of binary actuators within a robot structure is that they have two stable states where feedback control is not required. A binary actuator such as a pneumatic cylinder is low-priced, and has high robustness and good availability. As one binary digit is sufficient for the control of each binary actuator, the robot control can be achieved with a standard Programmable Logic Controller (PLC). These characteristics lead to a discrete robot workspace that requires methods for a defined positioning of robot's end-effector. Therefore, Chirikjian[1] aims high degree-of-freedom manipulators with many destination points inside a finite workspace, which allows obstacle-avoidance or pick-and-place tasks to be performed. These tasks imply a large number of binary actuators within the structure of manipulator. Therefore, Chirikjian and others[2–5] have published several approaches in synthesis, inverse and forward kinematics, efficient workspace generation, etc. for binary robots. There are several other motivations driving the field of binary robots. Plante *et al.*[6] have been researching new lightweight actuators to reduce the total weight of a binary robot. This is essential for robots that are developed to achieve tasks in outer space. In addition to minimizing the total weight, Sujan and Dubowsky[7] have designed a binary space robot with redundant binary actuators to enhance the robustness of the system. In case of a binary actuator failure, another actuator configuration can be used to reach the same desired end-effector position.

This contribution deals with a different approach to use binary actuators within robot structures. The objective is to create methods for the implementation and realization of an adapted task parallel robot with a minimum number of binary actuators. The simplest pick-and-place task consists of transporting an object from one position to another, which is done by a typical pick-and-place unit. These machines are either actuated by a linear binary actuator or a rotational drive in combination with a cam mechanism. Furthermore, several companies already offer serial structures with binary or continuous actuators based on modular robot components. These include the Gemotec System by SCHUNK or a modular handling system by EPS Automation,[8,9] which is based on the patent by Takahashi *et al.*[10] As the actuators of this open kinematic design are orientated along the Cartesian coordinates, manual corrections of destination points are easily achieved.

This work also focuses on simple handling applications that have more than two desired points by utilizing binary actuators in a parallel structure. The resulting structure has better stiff and a lower moved mass than the serial pick-and-place units.

Applications for this robot concept can be handling tasks such as sorting solar cells in different boxes after identifying their degree of efficiency. If the accuracy of such a robot is improved, it would be able to accomplish assembly tasks with high reliability, and could be a cost-effective solution. This would be of particular interest to small- and medium-sized companies, which could profit from affordable automation methods.

Moreover, a robot structure is built of modular components that allow a configuration that takes the specific task into account. This task is defined by customer's requirements and by the restrictions of environment. The specifications

* Corresponding author. E-mail: d.schuetz@tu-bs.de

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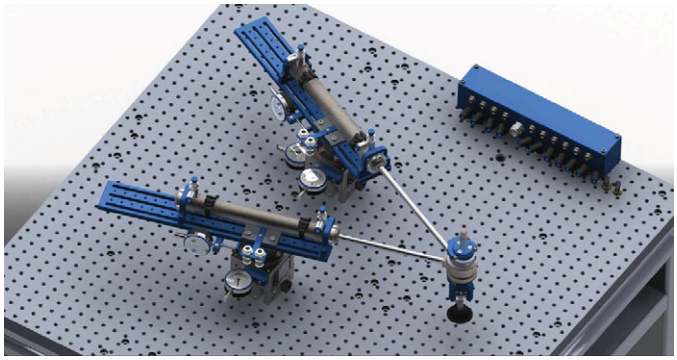


Fig. 1. (Colour online) CAD model of a binary parallel robot with RPRPR structure.

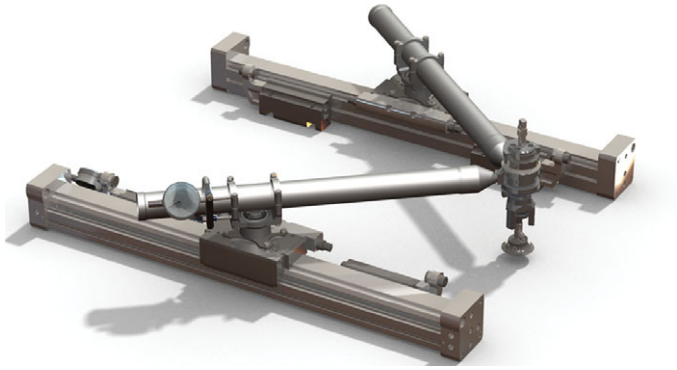


Fig. 2. (Colour online) CAD model of a binary parallel robot with PRRRP structure.

of a customer are, for example, the required payload of a manipulator, the cycle time of the task, as well as a given n point constellation that represents the desired end-effector positions. These initial conditions can be used for type synthesis and selection of suitable binary actuators in terms of stiffness, dynamics, and dimension availability. It is then necessary to synthesize the geometrical parameters of the structure, which include the necessary information for the installation of a robot. In ref. [11] the realization of a configuration of a parallel robot with three revolute joints (R) being driven by two binary actuated prismatic joints (P) in an RPRPR structure (Fig. 1) was presented. A specific synthesis algorithm was used to gain robot's parameters in dependence with the given four destination points which is followed by a new, mechanically based calibration technique.

One of the main differences between a binary robot and a typical industrial robot is the discrete nature of workspace. The discrete workspace is limited by the physical location of binary actuators, which can initially be different than the desired locations. In order to overcome this, a parameter calibration can be used to adjust the reachable n point constellation to meet design goals.

Plante and Dubowsky[12] have already published a calibration method for a parallel manipulator with binary actuation. This manipulator is applied for MRI-guided prostate cancer therapy. This system is actuated with bistable Dielectric Elastomer Actuators, which enable an elastic behavior for a safe human–robot interaction. The improvement of robot's accuracy is not based on the identification and minimization of the end-effector residual. Here 12 binary actuators are used to allow the end-effector to reach $2^{12} = 4096$ positions, which enable the robot to overcome discretization problems.

The idea of mechanical calibration is the modification of a typical kinematic parameter calibration within the actual system. After a mathematical model formulation of the structure with all relevant parameters, the structure is measured in all possible end-effector positions. The resulting residual between the nominal and actual end-effector positions is used for the identification of variable structure parameters. In order to achieve such a correction, additional mechanical adjustment components must be integrated inside a robot's structure. The basic concept has been validated with a prototype of a binary parallel robot with an RPRPR structure. The reachable accuracy after mechanical calibration during initial research for this structure is about 0.329 mm. This is a good result, especially with regard to a very low priced standard pneumatic cylinder types. A handicap of standard pneumatic cylinders is their fixed stroke lengths, and requires replacement of cylinders if a new task needs reconfiguration of robot structure with different stroke lengths. Moreover, it is not possible to adjust the geometrical parameter for mechanical calibration.

The objective of this work is to use a binaryparallel robot to accomplish a planar four-point task with better accuracy, and in half of the time. Therefore, the moving mass must be reduced and the stiffness of the structure can be achieved through the usage of rodless pneumatic cylinders inside of a PRRRP robot structure (Fig. 2). This type of pneumatic cylinder allows the stroke length to be adjusted.

The contribution starts with a section about the key aspects of this new robot concept, the ability of reconfiguration, and the ability of parameter adjustment. The next part deals with the regarded robot structure, its parameters, basic parts, such as links and joints, as well as additional components for adjustment. The geometric parameters are computed by a synthesis approach for the PRRRP kinematic structure, which takes into account the restrictions of a given test bed. Because of production and assembly tolerances, it is not possible to make a statement about robot's accuracy. Thus, a mechanical calibration must be used to overcome these differences and is the subject of the following section. After that the experimental model of a binary parallel robot with PRRRP structure is subjected to the presented calibration procedure so that a measurement of repeatability and accuracy of the robot has been accomplished for validation. The last section concludes this paper and gives a brief outlook on further studies.

2. Two Key Aspects for Usability of the Concept

The regarded robot concept is only practical and profitable for industrial use if the robot can be reconfigured for different tasks and its accuracy is sufficient for the given application requirements. Assuming that the original four-point constellation depicted in Fig. 3 could be reconfigured into the constellation in Fig. 4, a fast and easy method is needed to allow this transformation. This transformation

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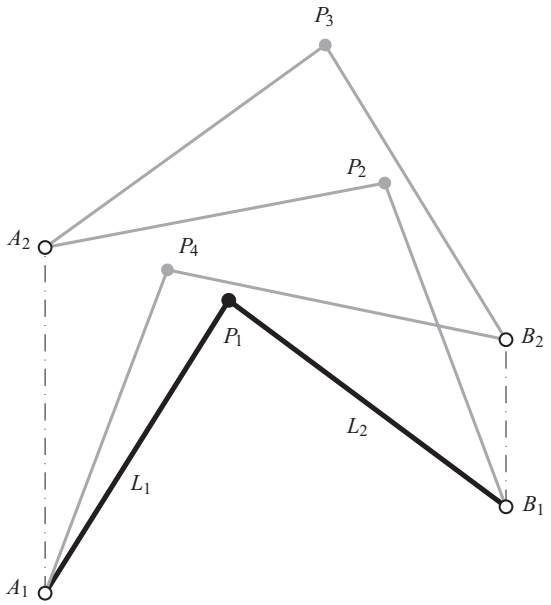


Fig. 3. The kinematic chain of a PRRRP structure with binary actuators and its four reachable end-effector positions.

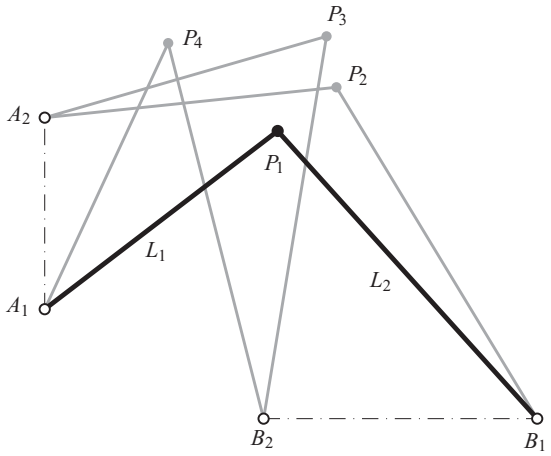


Fig. 4. The kinematic chain of a PRRRP structure with binary actuators and its four reachable end-effector positions after reconfiguration.

should happen within the installation space without a need to redesign any parts of the robot. The configuration and reconfiguration are determined by the synthesis of geometrical parameters (cf. Tab. I) on the basis of coordinates of n points of a specific task. In order to facilitate this process, the robot components, such as passive joints and links, should be of modular design and with dimension for maximum static and dynamic load.

Precise positioning of an end-effector, which ensures a problem-free assembly or a secure set down of parts, is not given after the installation of robot structure. Production and assembly tolerances need to be compensated by a parameter calibration. As no mathematical model of the robot is stored inside the PLC, the geometrical parameter offsets of the calibration procedure must be set by adjusting the robot structure parameters mechanically. To allow the correction of parameter values, additional adjustment components must be implemented inside the robot structure.

Table I. Geometrical parameters of PRRRP structure.

Description	Parameter
Coordinates of end-positions of first cylinder	$A_i = (x_{A,i};\ y_{A,i})$
Coordinates of end-positions of second cylinder	$B_i = (x_{B,i};\ y_{B,i})$
Link length	L_i
Coordinates of TCP	$P_j = (x_{TCP,j}; y_{TCP,j})$

Thus, a modular design of robot components allows a task-adapted configuration and reconfiguration of parallel robots with binary actuators, which makes possible a fast and easy installation of the robot structure. Because of the need of a task-depended accuracy, a mechanical calibration should be accomplished after installation by the correction of geometrical structure parameters with additional adjustment components.

3. Experimental Model of a Binary Parallel Robot with PRRRP Structure and its Components

In order to better clarify the synthesis approach (Section 4) and the mechanical calibration technique (Section 5), which are adapted to the PRRRP structure, the binary robot experimental model is first presented. An understanding of the test bed conditions and construction is helpful to comprehend the following sections.

3.1. The PRRRP kinematic structure

The available test bed allows different kinematic structures to be created on a square breadboard with an edge length of one meter. The experimental rig can simultaneously support up to four pneumatic cylinders with compressed air. The control of the actuators is realized by a standard PLC in combination with end-position sensors. The regarded planar five-bar manipulator of this work is based on a PRRRP structure as presented in Fig. 2. The main disadvantages of standard piston rod-based pneumatic cylinders are their fixed stroke lengths and reduced stiffness when the piston rod is extended. To reconfigure the robot's structure for a new four-point constellation, pneumatic cylinders with different stroke dimensions are required. To overcome this drawback, pneumatic cylinders with rodless piston are utilized as binary prismatic actuators. The piston is connected to a slide to which links and joints can be directly mounted. With regard to the entire linear actuator, the moving masses are only a small portion of the total mass, thus allowing a high dynamic movement of the slide. The end-positions of the slide can be adjusted within the maximum stroke length by mechanical end-position limiters. Thus, positioning one coordinate of parameters A_i and B_i in axis direction can be set without self-developed components. The other coordinate can be adjusted by a linear stage (Fig. 6) with one DOF.

In order to increase the flexibility of robot, a clamping mechanism has been introduced into the rotational element, which joins the structure to the pneumatic slide (Fig. 5). Furthermore, the variation of the link length L_i can be realized by sliding the tube inside this bracket.

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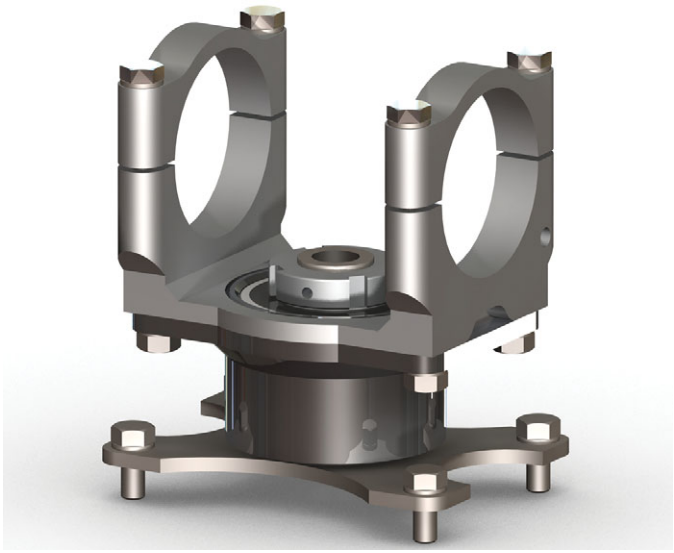


Fig. 5. (Colour online) Design of a revolute joint with a bracket to connect tubes of a robot structure.

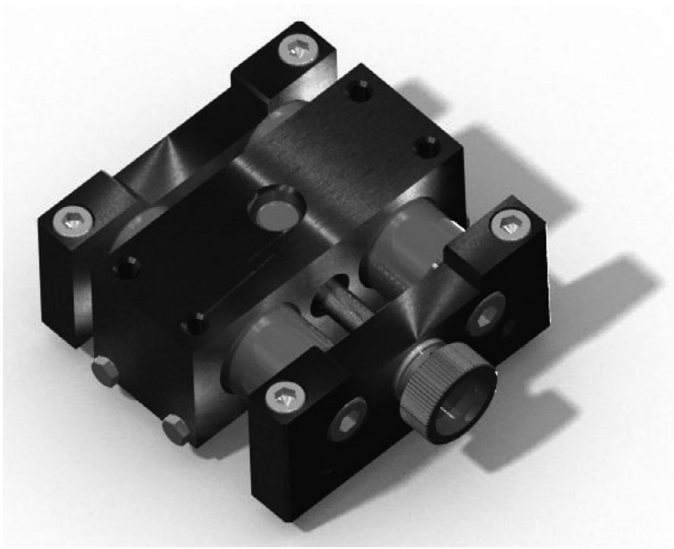


Fig. 6. Self-designed manual linear stage for adjustment with one degree-of-freedom.

The combination of adjustable link lengths L_i and end-position adjustments inside the basis kinematic structure (Fig. 7) enables the correction of four parameters of each kinematic chain. In (Fig. 8) the kinematic structure with additional components is shown. The extended model of a five-bar manipulator can be used for the synthesis of geometric parameters with regard to a given four-point constellation.

4. Adapted Task Synthesis

The synthesis of geometric parameters of the PRRRP structure for a specific four-point task is based on geometric restrictions of a closed kinematic chain. For a reproducible procedure, the first step is sorting the destination points by finding their minimal connection length. As illustrated in Fig. 9, the four destination points P_j, where $j = 1, \ldots, 4$, have been numbered in a counterclockwise manner. As two

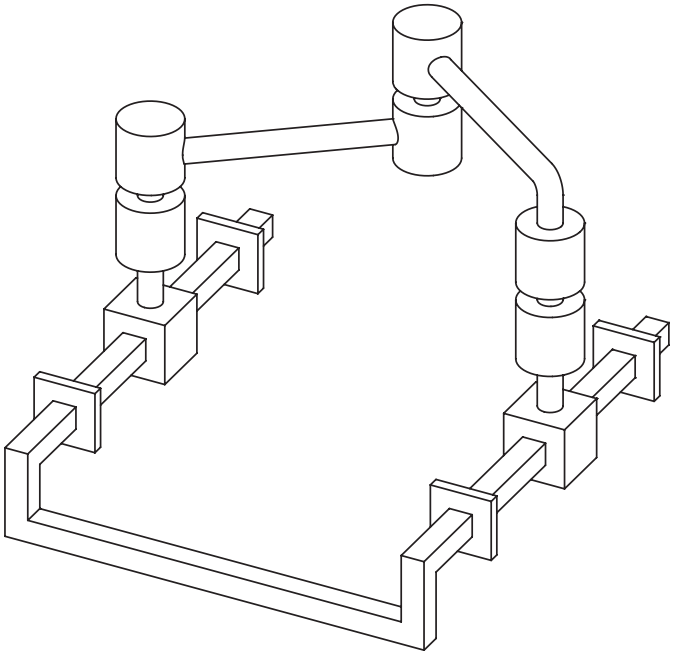


Fig. 7. Kinematic chain of a PRRRP structure.

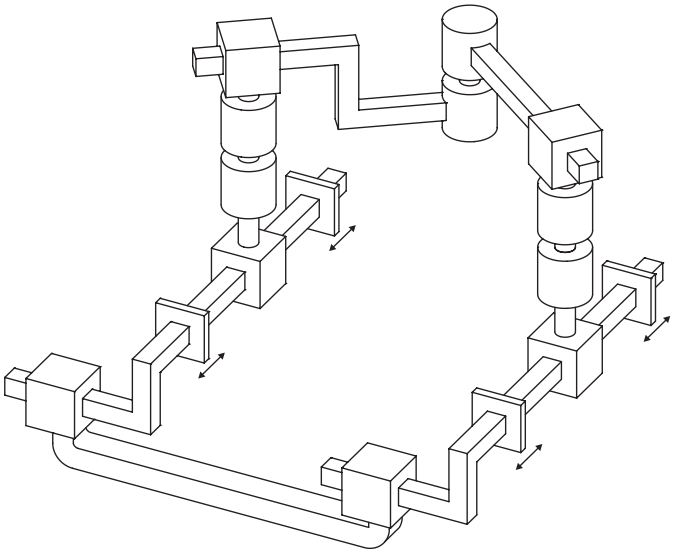


Fig. 8. Kinematic chain of a PRRRP structure with additional adjustment components.

destination points have a common instantaneous center of rotation, the cylinders' end-positions must then lie on a perpendicular bisector (cf. Figs. 10 and 13) of each side of the quadrilateral.[13]

Because of the infinite possible end-position solutions on the perpendicular, a solution can be found by defining the link of length L_i for one chain of the structure. The approach within this contribution sets the start link length $L_{i,0}$ to the minimal link length $L_{i,\min}$ which is defined by the restrictions of the environment. The intersection of the circle with radius $L_{i,\min}$ and its center on one of the related points P_j leads to two theoretical solutions for one end-position of the first cylinder (Fig. 11). Furthermore, Fig. 12 illustrates the solutions of other end-positions of the first cylinder.

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Fig. 9. Four given destination points of a specific task.

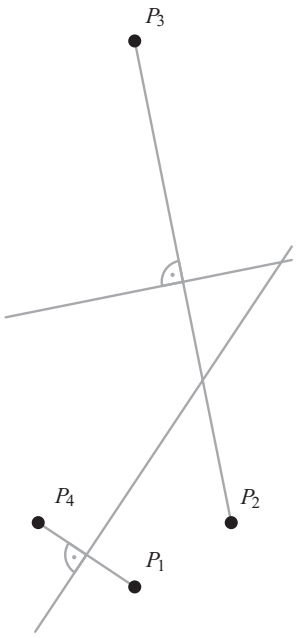


Fig. 10. Perpendicular bisector to achieve end-positions of first cylinder.

On the opposite side, the two solutions $B_{1,1}$ and $B_{1,2}$ on the perpendicular of $\overline{P_1 P_2}$ and $B_{2,1}$ and $B_{2,2}$ on the perpendicular of $\overline{P_3 P_4}$ can be obtained with the same procedure which represents solutions of end-positions for second cylinder (Fig. 13). One possible end-position configuration leads to a structure design shown in Fig. 14, which allows to reach the four given destination points P_j of Fig. 9.

For an adapter-free installation, the cylinders must be mounted vertically or horizontally on the plane of the breadboard grid (Figs. 3 and 4). Therefore, an optimization procedure is used (Eq. (1)) to find four solutions for each cylinder by varying the related link length L_i so that the

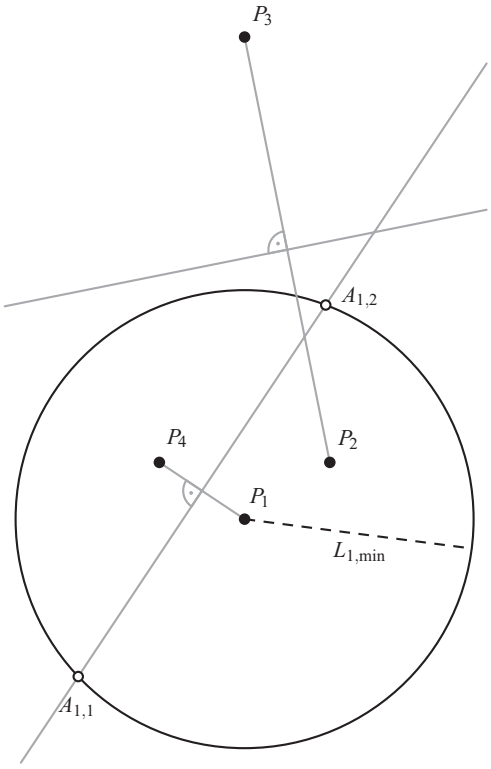


Fig. 11. The intersection $A_{1,1}$ and $A_{1,2}$ of the circle with radius $L_{1,\min}$ and its center on P_1 leads to two solutions for one end-position of first cylinder.

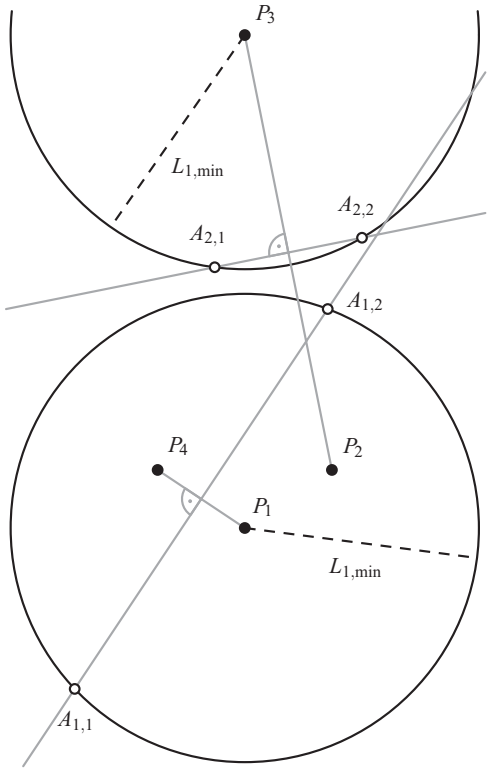


Fig. 12. The intersection $A_{2,1}$ and $A_{2,2}$ of the circle with the same radius, i.e., $L_{1,\min}$ and its center on P_3 leads to two solutions for the other end-position of first cylinder.

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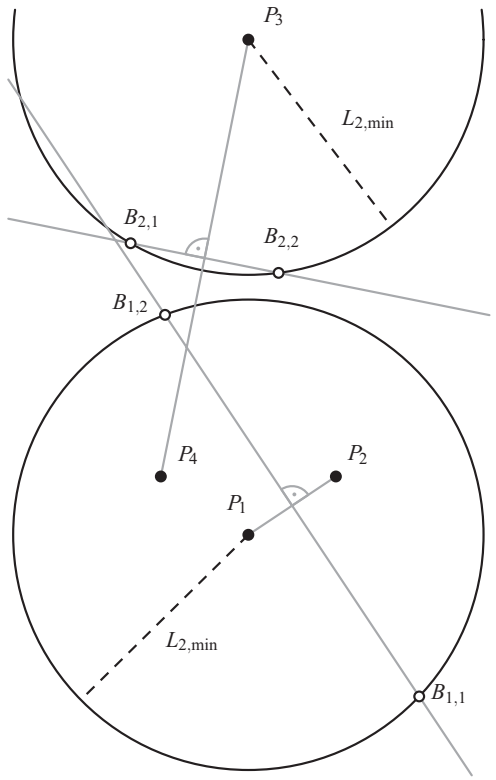


Fig. 13. The intersection $B_{i,m}$ of circles with radius $L_{2,\min}$ and their centers on P_1 and P_3 lead to two solutions for each end-position of second cylinder.

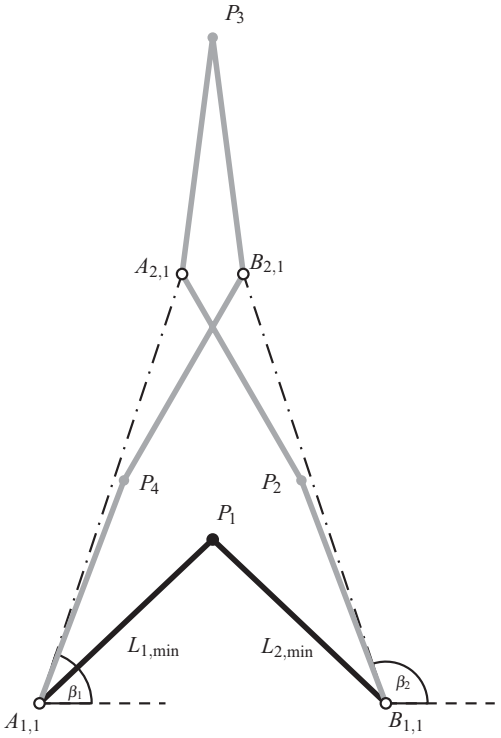


Fig. 14. The robot structure with one possible configuration of end-positions and minimal link lengths $L_{i,\min}$.

structure fulfills specific conditions,

$$\min_{L_i} = \alpha - |\beta_i(L_i)|. \tag{1}$$

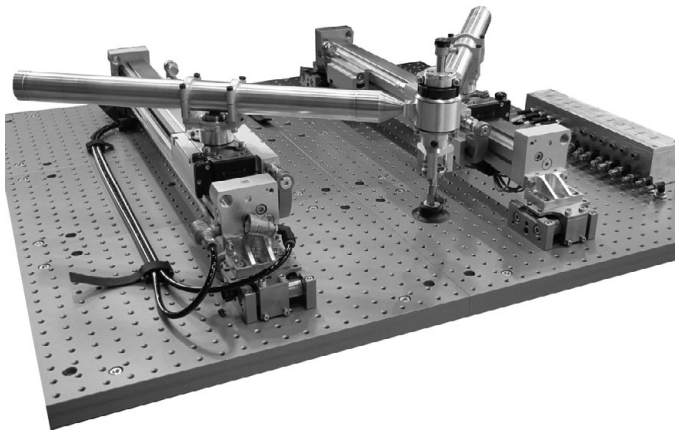


Fig. 15. Experimental model of a binary parallel robot with a PRRRP structure.

The actual parameter set **k**, which includes the link length L_i, leads to a cylinder alignment β_i, which is subtracted from angle α, where α represents the desired cylinder alignment of 0° or 90°, which can be reached by the minimization of difference of α and β_i.

The next step is to check the validity of each cylinder, as there is no solution if the link length is less than the half of the side of the quadrilateral, as described in Eq. (2),

$$L_i > \frac{1}{2} \cdot \overline{P_j P_{j+1}}. \tag{2}$$

After checking the validity of link lengths, the remaining solutions of one cylinder are combined with the usable solutions of the other cylinder. Because of environment restrictions, such as a limited installation space, angle restrictions, etc., and kinematic correlations, such as collisions between components of the structure, the solutions must be checked against every defined condition. After this procedure the remaining solutions represent suitable parameter sets **k** for the regarded robot structure.

In case that there is no remaining suitable parameter set, the user can be advised that either the environment must be changed or the coordinates of one task point must be set free. In the case in which one destination point is variable, an already presented Achimedean spiral algorithm moves that point until a suitable solution can be found.[11]

5. Mechanical Calibration Method

One suitable parameter set **k**, which results from the adapted task synthesis method of Section 4, enables the installation of a robot structure that fulfills the workspace requirements. Because of production and assembly tolerances, the robot most likely will not be able to fulfill the needed accuracy of the application. Therefore, additional components for adjustment are implemented in the prototype of a parallel robot with PRRRP structure as shown in Fig. 15.

However, the parameter correction is not as intuitive as it is for a serial robot with two binary actuators, and thus a calibration procedure is required. Because of the discrete manner of a robot, it is not possible to correct parameters, as the kinematic model is not implemented inside of the

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PLC, and thus a mechanical calibration is needed. The proposed mechanical calibration is based on a common robot parameter calibration,[14,15] with changes in the last two steps.

The mechanical calibrations are divided as follows:

- Mathematical model formulation,
- Measurement,
- Variable parameter identification, and
- Mechanical correction.

It is important for the mathematical model formulation that there is a differentiation between fixed parameters $\mathbf{k}_f$ and variable parameters $\mathbf{k}_v$ inside a kinematic model. Fixed parameters $\mathbf{k}_f$, such as the stroke of the standard pneumatic cylinder, which enables movement of the gripper in the direction of z-axis, cannot be adjusted, as no related additional components are implemented inside the robot structure. Even though these parameters can be identified within an optimization procedure, it is not possible to correct them with the considered structure. For this reason only variable parameters $\mathbf{k}_v$, which are adjustable by additional components, must be identified within the optimization procedure.

The calibration progress starts with the measurement of actual end-effector positions of a binary parallel robot. The coordinates of four points P_j of the prototype with a PRRRP structure are gathered with a laser tracker. This measurement system does not fit the concept of this low-priced binary parallel robot, but it is available and suitable for this task. Moreover, the development of other measurement methods will be the subject of future research.

The difference between the nominal end-effector positions $P_{j,n}$ and the measurement data, which represents the actual end-effector positions $P_{j,a}$, can be written in a residual vector $\mathbf{r}$. The residuals depend on variable parameters of the structure as shown in Eq. (3),

$$r_j(\mathbf{k}_v) = P_{j,a} - P_{j,n}(\mathbf{k}_v). \tag{3}$$

The multiplication of the residual vector $\mathbf{r}$ with its transposed vector leads to a scalar F (cf. Eq. (4)), which can then be minimized using an optimization algorithm,

$$F = \mathbf{r} \cdot \mathbf{r}^T. \tag{4}$$

The scalar F and the residuals r_j become zero if the actual end-effector positions are consistent with nominal positions. Because of the fact that the nominal end-effector positions represent the desired points of a specific task, the actual end-effector positions must be corrected instead of nominal positions as it is typically done for robots with a continuous workspace. Therefore, differences between the nominal variable parameter values $\mathbf{k}_v$ and the optimized values $\mathbf{k}_{v,\mathrm{opt}}$ are used to achieve the values for adjustment, $\delta\mathbf{k}_{v,\mathrm{opt}}$, as shown in Eq. (5),

$$\delta\mathbf{k}_{v,\mathrm{opt}} = \mathbf{k}_v - \mathbf{k}_{v,\mathrm{opt}}. \tag{5}$$

The parameter values for adjustment $\delta\mathbf{k}_{v,\mathrm{opt}}$ can be directly implemented inside the robot structure by using additional adjustment components (cf. Fig. 8).

6. Validation

In this section the validation of presented methods has been accomplished with the presented prototype of a binary parallel robot. The necessary parameter set for the installation of a robot is received by executing the adapted task synthesis of Section 4. As described in Section 5, the four-point constellation has been measured using a laser tracker. The measurement procedure is based on the European Norm ISO 9283, *Manipulating Industrial Robots – Performance Criteria and Related Test Methods*, which should ensure the comparability of the found characteristic data.[16] The important criteria of the regarded robot concept are repeatability RP and accuracy AP.

6.1. Repeatability

The repeatability of a robot can be obtained by measurement of minimum 30 times at point P_j. The value RP at each point P_j is defined as the mean square error $\bar{l}_j$ of 30 points plus the standard deviation S three times,

$$RP_j = \bar{l}_j + 3S, \tag{6}$$

where

$$\bar{l}_j = \frac{1}{30}\sum_{o=1}^{30}\sqrt{(x_{j,o} - \overline{x}_j)^2 + (y_{j,o} - \overline{y}_j)^2}, \tag{7}$$

and

$$S = \sqrt{\frac{\sum_{o=1}^{30}(l_{j,o} - \bar{l}_j)^2}{p-1}}. \tag{8}$$

In Fig. 16 the resulting repeatability measurement can be seen. Here the radius of each circle is the resulting RP_j value. The largest value of RP_j defines the repeatability RP of the entire robot, which is $RP \approx 0.032$ mm.

6.2. Accuracy

The accuracy AP of an industrial robot is defined by the difference between the desired or nominal end-effector position $P_{j,n}$ and the average value of the measured or actual end-effector positions $\overline{P}_{j,a}$. The accuracy of an uncalibrated robot is not yielding to repeatable values, as AP depends on the quality of the robot's installation and machining errors. Figure 16 illustrates the accuracy AP_j of each end-effector position P_j after mechanical calibration. Analogous to repeatability, the accuracy AP of the entire robot is defined by the largest value of AP_j for four points. The accuracy of the prototype of a binary parallel robot with PRRRP can be enhanced with the method of mechanical calibration and additional adjustment components to $AP \approx 0.141$ mm.

7. Results

The presented adapted task synthesis approach allows differentiation between user requirements and physical restrictions. The advantage of this separation is the opportunity to pursue different strategies to find a parameter set when the given requirements and restrictions prevent a suitable solution. The prerequisite to apply one of these

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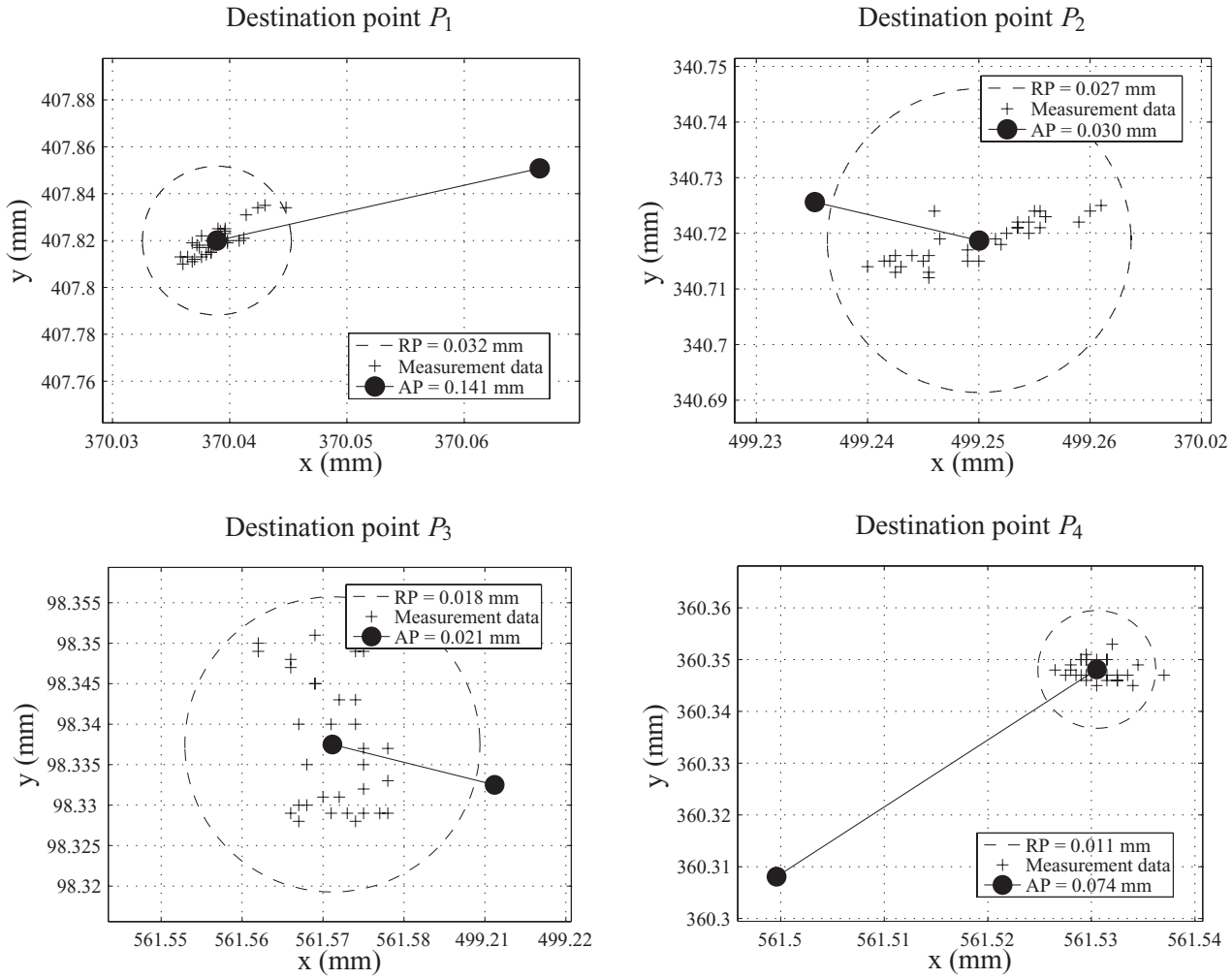


Fig. 16. Experimental repeatability and accuracy results of a prototype of a binary parallel robot with a PRRRP structure.

strategies is the freedom to change these restrictions, for example, the extension of available installation space, or the requirements such as the position of one destination point P_j so that the basic objective of a specific task can be achieved. If it is not possible to change the coordinates of one point P_j or to customize the restrictions, a type synthesis can be used to find a suitable kinematic structure, for example, with more than two binary actuators.

The accomplishment of the presented mechanical calibration method has been validated using a binary parallel robot, which has been introduced in Section 3. In comparison with the results of a prototype with an RPRPR structure ($RP \approx 0.036$ mm and $AP \approx 0.329$ mm), it has been shown that the repeatability of both structures is nearly the same. However, the accuracy of the structure that uses pneumatic cylinders with rodless piston is significantly better than of the structure with standard pneumatic cylinders. The ability to adjust all relevant parameters of each kinematic chain enhances the mechanical calibration results. In contrast, there has been no additional component intended to adjust the stroke of the standard pneumatic cylinder of the RPRPR structure. The limiting factor that prevents an even better accuracy of the presented robot is the precision of manual adjustment components, especially the cylinder end-positions are locked by a nut which is error-prone. Moreover, the progress of mechanical calibration with manual parameter adjustment is very time-consuming and should be improved in future research.

8. Conclusions

This contribution is focused on the methods of synthesis for configuration and reconfiguration, as well as calibration to ensure sufficient accuracy of planar binary parallel robots with a minimal number of actuators. A prototype of a binary parallel robot with the well-known PRRRP structure is actuated by rodless pneumatic cylinders and is used to validate an adapted task four-point synthesis approach as well as the technique of mechanical calibration.

The essential accomplishment of these methods is based on the fact that this type of robot has a discrete workspace with a minimum of reachable end-effector positions, which must fit the task-specific destination points. The presented synthesis approach is based on geometrical relations and allows the generation of a parameter set according to a given four-point task. By the use of additional components for parameter adjustment, the mechanical calibration method has been applied to the regarded binary parallel robot to enhance

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its accuracy. Further studies will focus on new methods that allow a faster and cheaper, and improving the precision of the mechanical parameter adjustment.

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