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Automatic Kinematic Calibration of a Modular Gantry-Tau Parallel Robot from a Kinematics Point of View

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Abstract— **A method for computer assisted kinematic calibration of a modular Gantry-Tau parallel robot is presented and tested in an experiment. A computer tool developed executes the first step of a kinematic calibration, the choice of appropriate measurement points, using *a priori* knowledge about kinematic parameters, e.g. obtained with a measuring tape. This step is performed by intersecting the robot's kinematic workspace and the area surveyable by the measurement device and overlaying it with a grid of a desired number of measurement points. A simulation determines automatically whether the choice leads to an accurate calibration and outputs a trajectory readable by a robot controller. In a calibration experiment it is shown that the method gives results with an accuracy comparable to that of manual calibration. The method allows non-experts to execute kinematic calibration of modular robots after reconfiguration thus making possible the use of modular robots in small size enterprises where such robots can answer the need for flexibility required with regularly changing tasks.**

I. Introduction

Although today most robots used in industry have serial kinematics, the use of parallel kinematic manipulators (PKMs) is becoming more and more widespread. An example of the growing use of parallel robots in industry is the ABB Flexpicker [1]. With parallel structures, higher stiffness can be achieved with less weight, which makes higher accelerations possible. However, most parallel robots have a smaller workspace than typical serial manipulators.

Figure 1 shows the Gantry-Tau PKM [2], which is a Gantry variant of the 3 degree-of-freedom (DOF) Tau PKM [3] based on an ABB patent [4]. Reference [5] presents a slightly different Gantry-Tau PKM which unlike [2] has a variable end-effector orientation. The Gantry-Tau PKM has the advantage of a larger working range than most parallel robots but still provides the high stiffness and high achievable accelerations of a parallel robot.

The Gantry-Tau PKM also has the potential to meet the needs of small and medium size enterprises (SMEs). Today, robots are mostly used in large enterprises, where a robot installation is optimized for one task which is often executed for years, e.g., a welding robot in the production line of one specific automobile type. As SMEs produce smaller lots, robots for SMEs need the flexibility to fit constantly changing tasks. Since robots used in industry today do not have an adjustable geometry, new robot concepts are needed to adapt robot technology to SME needs and thus make SMEs more competitive [6]. A modular robot which is reconfigurable according to varying tasks is therefore needed. The Gantry-Tau PKM is promising in this regard. It can be designed in a modular way so that the framework can be adjusted to specific tasks [7]. However, problems can arise for SMEs because every reconfiguration of a robot requires a new kinematic calibration and such recalibrations tend to be difficult for the non-expert SME staff.

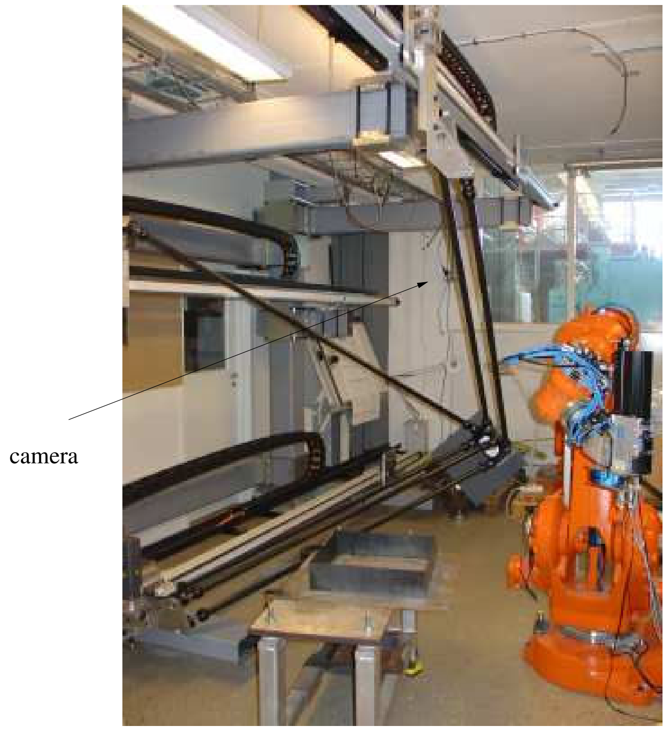

Fig. 1. Gantry-Tau prototype (in the left of the picture) with mounted pattern plate for calibration using a camera (mounted to the left of the window) at the Robotics Lab at LTH, Lund University; the picture shows as well other experiment equipment narrowing the Gantry-Tau's workspace

Tools are thus needed to assist the non-expert SME staff execute multiple kinematic calibrations. Traditionally, a robot is delivered as an optimized entity by the robot manufacturer or built as a prototype for research purposes. In both cases the robot geometry is not changed and kinematic calibration, which needs to be performed only once and is done by robot experts, the manufacturer or a researcher, see e.g. [8] for the kinematic calibration of a PKM or [5] for the kinematic calibration of a Gantry-Tau robot. Such kinematic calibrations include several manually performed steps which require

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expert knowledge and have to be re-done for the calibration of a changed geometry, such as the choice of measurement poses or the analysis of the measurement data. However, SME owners do not want to pay a calibration expert every time they change the robot geometry, but seldom have the required knowledge and experience. So this knowledge and experience has to be provided without such expense.

In this article, a computer-assisted calibration method for a reconfigurable Gantry-Tau PKM is presented. A tool has been developed which performs the selection of measurement points according to the chosen measurement device and the robot's *a priori* workspace, which is based on initial knowledge about the kinematic parameters resulting e.g. from a tool optimizing the robot geometry for a specific task [7]. The tool also includes automatic evaluation of the chosen measurement points by simulation and the output of a robot trajectory for calibration in a form readable by the robot controller.

The article is organised as follows: In Section II, the Gantry-Tau kinematics are presented, in Section III an automated calibration method for the Gantry-Tau PKM is proposed, Section IV shows experiment results and Section V concludes with a discussion.

II. GANTRY-TAU KINEMATICS

The Gantry-Tau PKM (Fig. 2) consists of three kinematic chains. Each chain includes a prismatic actuator which is connected to the end-effector plate via a link cluster. The actuators are implemented as carts moving on tracks. The altogether six links are distributed to the clusters in a 3-2-1 configuration and connected to carts and end-effector plate by spherical joints. The placement of the passive joints on plate and carts is such, that the links belonging to one cluster form parallelograms, which leads to a constant end-effector orientation. The robot has therefore three purely translational degrees of freedom (DOF).

The kinematics problem is solved in [2] for parallel actuator axes and in [9] for actuator axes with arbitrary orientation. As the 3 DOF robot has fixed orientation, it is sufficient to consider only one link for each of the 3 clusters.

Figures 2 and 3 illustrate the kinematic parameters used. (X_i^0, Y_i^0, Z_i^0) and (X_i, Y_i, Z_i) are reference and actual position of cart i, given in global frame coordinates. L_i is the link length of link cluster i and q_i cart i's distance from its reference position. (X, Y, Z) denotes the tool center point (TCP) position and $(d_{i,x}, d_{i,y}, d_{i,z})$ link i's attachment point on the end-effector plate, given in the TCP frame.

The closure equation for link cluster i considering orientation errors of the tracks is then:

$$L_i^2 - (\Delta X_i^2 + \Delta Y_i^2 + \Delta Z_i^2) = 0, \quad (1)$$

where $(\Delta X_i, \Delta Y_i, \Delta Z_i)^T$ is the vector along link i:

$$\begin{aligned} \Delta X_i &= X + d_{i,x} - X_i \\ \Delta Y_i &= Y + d_{i,y} - Y_i \\ \Delta Z_i &= Z + d_{i,z} - Z_i \end{aligned} \quad (2)$$

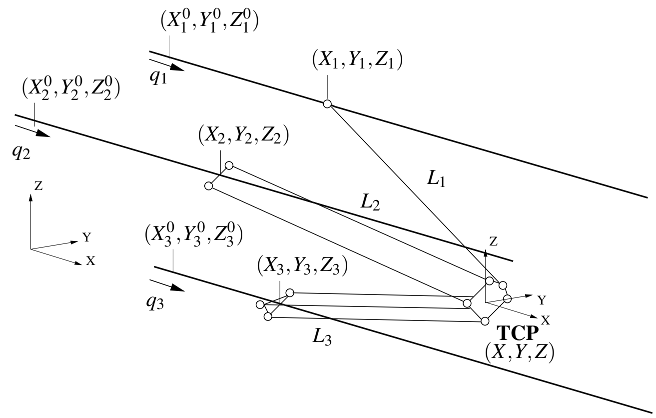

Fig. 2. Schematic Gantry-Tau PKM with parameter and variable notation; all coordinates are given in the global frame coordinates.

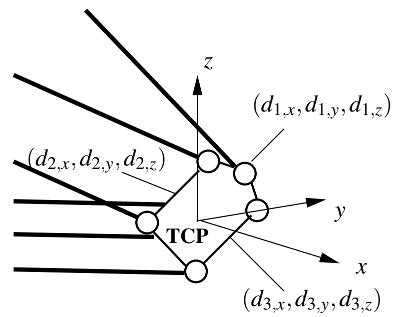

Fig. 3. Schematic Gantry-Tau PKM mounting interface with parameter and variable notation; all coordinates are given in the TCP coordinate frame, which has the same orientation as the global frame.

With arbitrary track orientation, (X_i, Y_i, Z_i) can be expressed as:

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} = \begin{pmatrix} X_i^0 \\ Y_i^0 \\ Z_i^0 \end{pmatrix} + \begin{pmatrix} c_{i,x} \\ c_{i,y} \\ c_{i,z} \end{pmatrix} q_i, \quad (3)$$

where $(c_{i,x}, c_{i,y}, c_{i,z})$ is the unit vector along track i in positive q_i direction.

The inverse kinematic problem can be solved independently for each kinematic chain. The articulate coordinate q_i is obtained by solving the quadratic equation (1) for q_i. The solution is not cited here for space reasons.

The direct kinematics problem can be solved according to the stepwise solution in [2]. To obtain the TCP position from articulate coordinates q_i, the intersection of two links is first calculated and the resulting circle is then intersected with the third link.

The equations show that the kinematics can be expressed by 7 parameters per kinematic chain: the link length L_i, the vector in track direction $(c_{i,x}, c_{i,y}, c_{i,z})^T$ and an offset in x, y and z direction $(X_{i,\text{offset}}, Y_{i,\text{offset}}, Z_{i,\text{offset}})^T$, which accumulate offsets of the joints on tracks and end-effector plate:

$$\begin{aligned} X_{i,\text{offset}} &= X_i^0 - d_{i,x} \\ Y_{i,\text{offset}} &= Y_i^0 - d_{i,y} \\ Z_{i,\text{offset}} &= Z_i^0 - d_{i,z} \end{aligned} \quad (4)$$

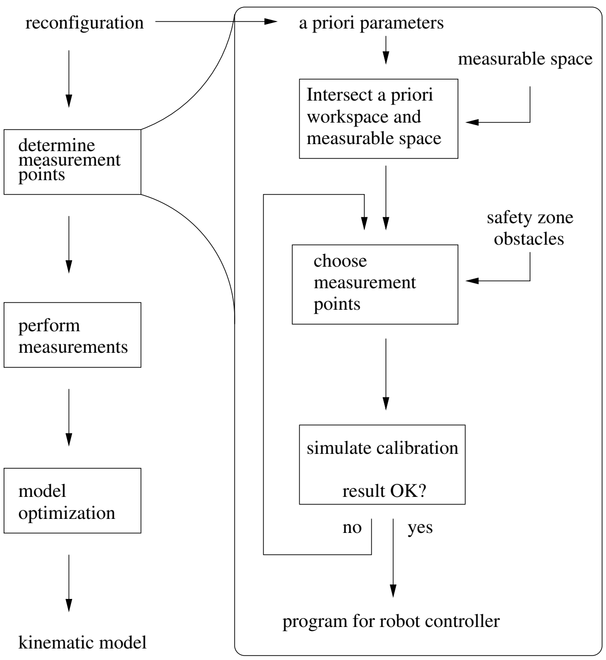

Fig. 4. The calibration algorithm with the measurement point selection presented

III. Assisted Kinematic Calibration

In this section, a new, computer assisted method is presented that enables non-expert technicians to calibrate the kinematic model of a reconfigurable parallel robot (Fig. 4). In the first step, the workspace of the robot is intersected with the space measurable by the chosen measurement device. Next, the resulting space is filled with measurement points and a simulated calibration evaluates whether the chosen points result in accurate parameters. The tool then generates a trajectory in a form readable by the robot controller and the kinematic calibration is performed.

Workspace Calculation

With the aid of *a priori* kinematic parameters, the robot's working range is calculated. These parameters can result from rough manual measurements or as an output from an optimization tool which reconfigures the robot geometry according to a changed task. The working range includes all points for which the inverse kinematics problem has a solution and the angles of the spherical joints are lower than a limit value. The determination of the kinematic working range is implemented as follows. First, a maximum conceivable workspace is roughly determined from the *a priori* parameters and the room dimensions and filled with a grid. To prevent self-collisions, the maximum conceivable workspace does not include the robot framework. The tool determines for each grid point whether the inverse kinematics has a solution. The grid point is considered part of the workspace if a solution exists and is such that the articulate coordinates are in a certain range, e.g., specified by track limits, and the deviation angles of the spherical joints are below a specified value.

Safety Zones

The resulting kinematic working range can additionally be narrowed by obstacles such as walls or other equipment in the workshop. Grid points colliding with obstacles are deleted from the workspace. In doing so even the dimensions of extra equipment such as a pattern plate for calibration with a camera is taken into account.

To prevent damage of the robot due to the uncertainty of the *a priori* parameters, the working range for calibration excludes a safety zone around obstacles, in the range of the spherical joint angles and at the limit of the kinematic working range. The safety zones for the obstacles and joint angles are directly included in obstacle zone and limit angle. To assure that measurement points have a certain distance to the kinematic workspace limit, grid points which do not have a minimum distance to grid points for which no kinematics solution exists are deleted from the workspace.

Measurable Area

The resulting working range is then intersected with the points the measurement device can record. The calculations include calibration devices mounted on the robot platform, e.g. a pattern plate for camera assisted calibration, as they may have a different orientation and an offset compared to the TCP and for some devices, such as the pattern plate, it is important to record the whole of a surface area. Here, a camera with fixed position and orientation is considered, with the pose and intrinsic camera parameters assumed to be known from before. Using a pinhole model of the camera, the tool tests for each workspace point whether the projection of the calibration pattern is inside the picture boundaries.

Measurement Points

The measurement points, i.e., the robot configurations in which the camera takes a picture, are then distributed in a regular pattern over the resulting workspace intersection. This is achieved by estimating the volume of the workspace intersection and calculating a new grid constant based on a desired number of measurement points. The intersection of robot and camera workspace is determined a second time using a new grid resulting in a desired number of measurement points.

Simulation and Experiment

Using the *a priori* parameters and the inverse kinematics solution, measurements for the kinematic calibration are simulated to evaluate the chosen measurement points. Each kinematic chain can be calibrated separately. As a cost function for the parameter optimization, the sum of the quadratic closure equation errors for link i is chosen:

$$C_i = \sum_{j=1}^{N} (L_i^2 - (\Delta X_{i,j}^2 + \Delta Y_{i,j}^2 + \Delta Z_{i,j}^2))^2 \quad (5)$$

The Jacobian matrix, i.e., the derivative of the cost function at the measurement points is calculated and its singular values and conditioning evaluated. The parameter optimization is performed after adding noise to the simulated TCP

TABLE I

KINEMATIC PARAMETERS OF GANTRY-TAU PKM

Description	Manual measurement	Calibrated
$L_1(m)$	2.05	2.0440
$X_{1,\text{offset}}(m)$	0.04	-0.0396
$Y_{1,\text{offset}}(m)$	0	0.0009
$Z_{1,\text{offset}}(m)$	1.44	1.4243
$c_{1,x}$	1	0.9641
$c_{1,y}$	0	-0.0209
$c_{1,z}$	0	-0.0087
$L_2(m)$	1.82	1.7547
$X_{2,\text{offset}}(m)$	0.25	0.2443
$Y_{2,\text{offset}}(m)$	-1.31	-1.2639
$Z_{2,\text{offset}}(m)$	1.46	1.3984
$c_{2,x}$	1	0.9768
$c_{2,y}$	0	-0.0331
$c_{2,z}$	0	-0.0216
$L_3(m)$	1.81	1.7770
$X_{3,\text{offset}}(m)$	0	0
$Y_{3,\text{offset}}(m)$	0	0
$Z_{3,\text{offset}}(m)$	0	0
$c_{3,x}$	1	1
$c_{3,y}$	0	0
$c_{3,z}$	0	0

measurements and the resulting parameters are compared to the *a priori* parameters. If the conditioning of the Jacobian matrix and the results of the optimization are in a reasonable range, the real calibration is executed, if not, the simulation is repeated with more measurement points. For evaluating the Jacobian matrix conditioning, the criterion presented in [10] was adapted and approved if

$$\frac{\sigma_{max}}{\sigma_{min}^2} < 200 \tag{6}$$

where σ_{max} and σ_{min} were the largest and smallest singular value of the Jacobian matrix.

IV. CALIBRATION RESULTS

The computer assisted calibration experiment was performed on the Gantry-Tau PKM prototype at the LTH Robotics Lab (Fig. 1). Table I shows the robot's kinematic parameters determined using a measuring tape. The coordinate system used here had its x-axis along track 3 and the z-axis is intersecting with track 1. The origin was defined so that the offset parameters for link cluster 3 are 0. The measurements were performed using a camera and a camera calibration toolbox for Matlab [11]. Calculations have been performed with Matlab. No adjustments in the pose selection process were made to the specific geometry of the prototype in order to simulate a newly reconfigurated robot.

The kinematic workspace was calculated using the *a priori* parameters resulting from manual measurement (see Table I). First, the maximum conceivable workspace was determined from the *a priori* parameters and track dimensions and filled with a grid with 10 cm spacing. Figure 5 shows the maximum conceivable workspace and the identified kinematic workspace. The joint angles were limited to 30°, which gave a safety interval of nearly 15° for the spherical joints used. The cart movement was limited to ±1 m from their reference

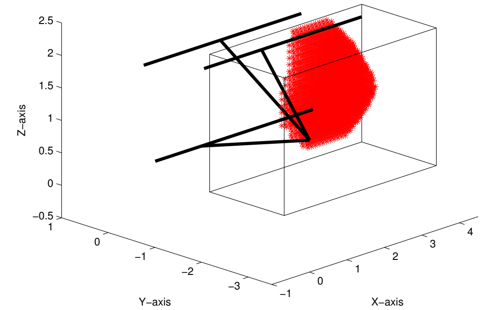

Fig. 5. Kinematic workspace of robot (star cloud) taking joint limits into account with approximate track positions (thick lines), links and maximum conceivable workspace (box).

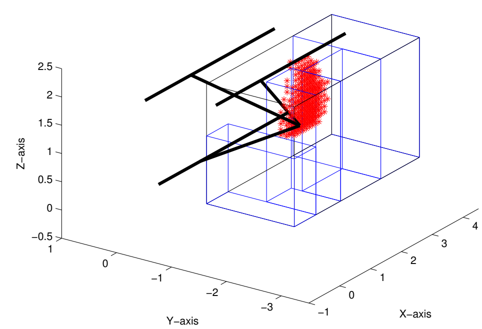

Fig. 6. Remaining workspace points after elimination of points colliding with obstacles or too near the kinematic workspace limit; the obstacle regions are marked as boxes inside the maximum conceivable workspace. The ratio between the remaining workspace and the kinematic workspace in Fig. 5 is 0.4.

position. The safety distance to the workspace limit was 10 cm.

In Fig. 1, the obstacles present in the robot lab, such as experiment equipment and an ABB IRB 2400 robot, can be seen. Regions around these obstacles were eliminated from the workspace. Figure 6 shows the remaining workspace points as well as the obstacle regions marked as boxes. They correspond to an experiment table, the ABB IRB 2400 robot, experiment equipment behind the robot and a palette with diverse work piece samples in the back of the room.

Figure 7 shows the measurable area of the camera in relation to the robot workspace calculated above. The measurable area was very roughly estimated based on a pinhole camera model. For this, a picture of the calibration pattern was taken and the pattern size on the image was measured. Knowing the pattern's distance from the focus using the camera calibration toolbox as well as the pattern's real size and the image size, the area projected on the image can be determined at any distance from the camera's focus. Although simple, this method was sufficiently accurate to identify the part of the robot workspace measurable by the camera. The camera

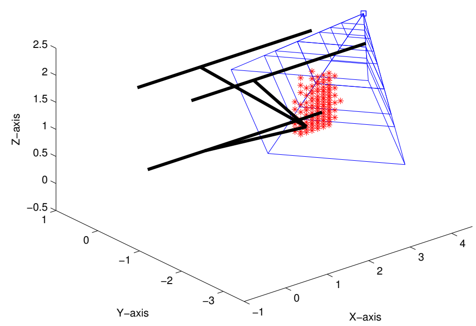

Fig. 7. The measurement points chosen together with the area recordable by the camera

Fig. 8. View out of the camera: the robot with the calibration pattern (in the right of the picture); in the left of the picture, obstacles consisting of experiment equipment and another robot can be seen.

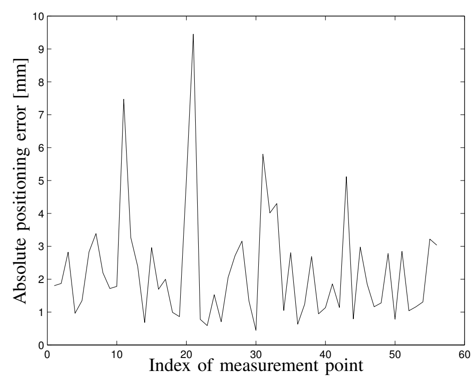

Fig. 9. Absolute positioning error of the identified kinematic model

pose was determined by estimating several TCP poses with the camera using the camera calibration toolbox, and then calculating the transition between global system and camera frame with the aid of the *a priori* parameters. As can be seen, the camera could record the complete robot workspace.

In simulations of the kinematic calibration of a similar Gantry-Tau robot [12], 50 measurement points were found to be sufficient. The desired number of measurement points was therefore set to 100, which includes 50 additional measurements for model validation.

Next, the measurement points for the calibration were chosen (Fig. 7). For that, the workspace was filled with a new grid with a grid length of 0.1367 m, which was calculated using the desired number of measurement points, 100, and an estimation of the workspace volume. 112 Measurement points were obtained for which articulate coordinates were calculated using the *a priori* parameters.

Next, a simulated kinematic calibration showed that the kinematic parameters can be estimated sufficiently well with the chosen measurement points for executing the real calibration. The evaluation of the Jacobian matrices gave for all tracks singular values between 0.3 and 64. Noise was added to the TCP measurement points before estimating the kinematic parameters. The resulting parameters differed less than the chosen limit value of 2 cm from the *a priori* parameters.

The results of the prototype calibration are shown in Table I. The RAPID program generated from the Matlab program was executed on the robot controller, the pictures taken with the camera (Fig. 8) were evaluated with a camera toolbox for Matlab. Every second measurement point was used for the parameter optimization, the remaining points to validate the kinematic model. The cost function after optimization was for all three tracks around 0.001 m^2, which corresponds to a mean error of about 4 mm for each measurement point.

Figure 9 shows the absolute positioning error when using the identified kinematic parameters in a direct kinematics model. The error was of the same order of magnitude as the camera's measurement accuracy. It attained 9.5 mm at one point but was mostly below 3 mm, its mean value being 2.3 mm. The peaks were distributed randomly in the robot's workspace and do not correspond to a certain direction or region in the workspace.

V. Discussion and Conclusion

Using only half of the 112 measurement points for calibration, the calibration results were shown to have an accuracy comparable to that with manual calibration. The positioning error of the validation data was at least partly due to the camera's measurement uncertainty which is suggested by the fact that it is of the same order of magnitude as the mean error per measurement after optimization.

Kinematic calibration of the Gantry-Tau robot using a laser tracker [9] resulted in a mean positioning error of 0.23 mm. As laser trackers are very accurate measurement devices [13], this error can be regarded as modeling error. This indicates that an important part of the resulting positioning error in this work is not due to modeling errors but due to the inaccuracy of the measurement device.

The advantage of the method presented compared to previous published work, e.g., [8] or [9], is the automatic selection of measurement points. This makes it possible to execute calibration without choosing appropriate measurement poses manually and thus, kinematic calibration can be performed by non-experts.

When selecting the measurement points, the tool has to find a compromise between safety and spreading the measurement points as wide as possible and thus probably obtaining a more accurate calibration result. Comparing Figs. 5 and 6, it can be seen that damage prevention narrows the workspace considerably. Moreover, a 15° safety interval for the joints angles seems rather large. During the experiment however, some joints approached their mechanical limit up to about 10° at a few poses, whereas collisions were not risked. Mechanical touch sensors can prevent damage of the joints, but with their use safety intervals should not be reduced as that can lead to experiment interruptions and less measurement points.

In principle, the calibration method presented can be applied for any kind of robot or measurement device. Both the calculation of the measurable space of the camera and the robot's kinematic model can be exchanged for corresponding calculations for other robots or measurement devices. Such adaptations include also the determination of how different robot geometries influence different values. The range of singular values and condition numbers of the Jacobian matrix in which the optimization gives a good result may vary from robot to robot. Different robot geometries may also have a different workspace edge sensitivity on parameter changes and thus need a different safety zone size.

Further research might include a tool for camera pose optimization. For a freely movable camera, the tool could easily be adapted to calculate a pose where the largest possible area of the robot workspace could be recorded. For a partly movable camera, the tool could, for example, optimize the orientation. This tool would then need to include an assistance for the camera placement, e.g., the superposition of the camera picture with a calculated desired picture, e.g., the projection of the calibration pattern as it is supposed to appear on the picture. The tool could also support other types of measurement tools. Optimization will be difficult if there are obstacles present in the room or the space where the camera can be placed is non-convex.

A possibility to increase the calibration accuracy would be to determine more measurement points than needed and then choose the best ones. This can easily be done by examining the influence of a certain measurement point on the singular values of the Jacobian matrix. It would as well be interesting to have an estimate of the model accuracy, both before and after calibration. Before calibration it would allow changes to be made before executing the calibration if the desired accuracy cannot be achieved, e.g. by increasing the number of measuring points or choosing a more accurate measuring device.

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