Robust Calibration Procedure of a Manipulator and a 2D Laser Scanner using a 1D Calibration Target

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Keywords: Mobile Robotics, Extrinsic Calibration, Mobile Manipulation, 2D Laser Scanner, LiDAR, Parameter Optimization.

Abstract: An accurate extrinsic calibration between a robots' exteroceptive sensors and its manipulator is essential for tasks such as mobile manipulation and tactile exploration. Especially for extrinsic calibration of a manipulators' end effector and 2D laser scanner, state-of-the-art approaches often require complex calibration targets or sensors which need to be mounted to the end effector. Therefore, such approaches are only suitable to a limited extent for use in mobile robotics. In this paper, we present a simple but effective approach to determine the six degrees of freedom transformation between the end effector of a serial manipulator and the center of a 2D laser scanner. In contrast to other approaches, our approach requires only a 1D target for calibration. Whereas complex calibration geometries often require a tool change for calibration, our approach is also applicable using practical objects like a drill mounted to the end effector. As a consequence, a tool change is not required for recalibration for many applications anymore. To evaluate the performance of our approach, we perform the calibration based on simulated as well as real data. We compare our results against the ground truth of a physically closed transformation chain using the lidars' CAD data.

1 INTRODUCTION

The scientific attention on autonomous mobile manipulators has been growing over the past years as the technology promises immense potential in the fields of industrial robotics, logistics or search and rescue scenarios. Especially the combination of perception and manipulation is promising for a multitude of applications. The environment of a mobile robot can be captured by a variety of different exteroceptive sensors such as RGB, thermal (Zeise. and Wagner., 2016)(Mehltretter et al., 2019) or hyperspectral cameras (Kleinschmidt and Wagner, 2018), laser scanners (Wulf and Wagner, 2003) as well as radar sensors (Fritsche and Wagner, 2017). Laser scanners are of particular relevance for mapping and localization because of their robustness and accuracy. In addition to sensors for environmental perception, mobile platforms are often equipped with various types of manipulators to interact with their environment. In order to perceive the environment as well as to interact with it autonomously, the perception of the environment must be combined with the movement of the manipulator. To put sensors and manipulators into a geometric context, they have to be intrinsically and extrinsically calibrated. Depending on the desired task as well as the sensor technology used, the specified accuracy and tolerances must be adhered to. Additional requirements may relate to the simplicity and robustness of the calibration procedure since the laboratory or industrial settings vary depending on the environmental conditions or the professionalism and training of the operator.

This paper focuses on the calibration of a 2D laser scanner and a manipulator. Especially for extrinsic calibration of a manipulators' end effector and 2D laser scanner, state-of-the-art approaches often require complex calibration targets (Antone and Friedman, 2007) or additional sensors (McIvor, 1999) which need to be mounted to the end effector. Therefore, such approaches are only suitable to a limited extent for use in mobile robotics. Whereas complex calibration geometries often require a tool change for calibration, our approach is also applicable using more practical objects like a drill mounted to the end effector (Gray et al., 2013). As a consequence, a tool change is not required for recalibration for many applications anymore. A calibration is thus also possible

Alberts, J., Kleinschmidt, S. and Wagner, B.
Robust Calibration Procedure of a Manipulator and a 2D Laser Scanner using a 1D Calibration Target.
DOI: 10.5220/0007946701120119
In *Proceedings of the 16th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2019)*, pages 112-119
ISBN: 978-989-758-380-3

while a robot is in use, which is a particular advantage in the context of mobile robotics. We show that our approach is robust and accurate as well as simple to use. For this reason, we evaluate our approach based on simulated and real experiments.

2 RELATED WORKS

Robot calibration procedures have been studied extensively over the past decades. Regarding mobile manipulators there exist calibration procedures concerning the intrinsic calibration of the manipulator as in (Bennett et al., 1991) or (Wieghardt and Wagner, 2017) but also procedures for extrinsic calibration of manipulator and exteroceptive sensors.

The transformation between a manipulator and a laser scanner can be determined by ascertaining the relation between the known movement of the manipulator and the corresponding measurements of the laser scanner. In principle two approaches are investigated in the research community:

1st) An additional exteroceptive sensor is attached to the manipulator. This additional sensor is calibrated to the laser scanner. The still missing transformation between the attached sensor and the manipulator needs to be determined as well.

The calibration between a laser scanner and a camera is examined in several works as (McIvor, 1999), (Mei and Rives, 2006), (Zhang and Pless, 2004). An advantage of these approaches is that calibration techniques of laser scanner and cameras are well established in the research community. The major drawback regarding mobile manipulators is, that an additional sensor is needed and a further calibration between manipulator and camera is neccessary. This problem is known as hand-eye-calibration problem and is investigated in several works as (Tsai and Lenz, 1989) or (Horaud and Dornaika, 1995).

2nd) A calibration target that is well known in its geometry is attached to the manipulator and moved within the laser plane. The calibration between the laser scanner and the manipulator can be determined by taking into account the known geometry of the calibration target, the movement of the manipulator and the measurements of the laser scanner.

An advantage is that no additional sensor is needed for calibration. The drawback of this calibration principle is that the laser scanner measurements needs to be matched with the calibration target's geometry unambiguously which requires a calibration target of appropriate geometry and size.

(Pradeep et al., 2010) examine an approach, using the intensity of the moving end effector in a 3D laser scan. This approach requires a 3D laser scanner which is capable of measuring intensities. In (Antone and Friedman, 2007) a 3D calibration target is used to determine the needed transformation with a single measurement of a 2D laser scanner. This method uses complex calibration targets of different sizes depending on the desired accuracy of the calibration. (Andersen et al., 2014) present a method that uses a 2D calibration target. The calibration target is moved within the spanned area of the 2D laser scanner and the transformation is determined. This method has been evaluated in simulation.

In this paper, we propose a calibration procedure that determines the transformation between a manipulators base and a two 2D laser scanner. Therefore, we move a 1D geometry within the spanned plane of the 2D laser scanner. In contrast to state-of-the-art calibration procedures this paper examines a method that does not require additional sensors, using a calibration target which has a much simpler geometry compared to existing approaches. Furthermore, because of the 1D nature of the object, alternative objects as drills can also be used for calibration which makes our approach independent of specialized calibration bodies which are needed for other approaches.

The suggested approach simplifies the idea introduced in (Andersen et al., 2014) by using a less complex 1D calibration target. Whereas the approach presented in (Andersen et al., 2014) fits multiple features of the calibration targets' geometry simultaneously, our proposed approach only fits one intersection of the 1D calibration target with the laser plane at a time. The lower number of features for an individual measurement is compensated by repeated measurements of the targets' intersection for several configurations of the manipulator. Besides, in contrast to (Andersen et al., 2014), measurements of real experiments are used for evaluation to show the capabilities of our approach.

The calibration procedure does not require laboratory environment conditions and can be carried out by operators without professional skills. The error of the proposed calibration is lower than the tolerance of the deployed laser scanner emphasizing its practical relevance. As only a 1D calibration target is required the procedure is applicable using drilling tools already attached to the end effector.

In summarise the main contributions of this work are:

- Calibration procedure using a 1D calibration target and no additional sensor
- Applicable without calibration target when used with attached drilling tools

- Practical relevance due to the low error of calibration
- Simple and robust procedure in terms of applicability and environmental conditions

The rest of this paper is organized as follows: In Chapter 3 the problem formulation is provided containing the mathematical fundamentals, the system modeling such as the methodology of the proposed approach. In Chapter 4 the experimental evaluation is presented. The Methodology of the experimental setup and evaluation is described and the results of simulated and real experiments are introduced. The conclusion is summarised in Chapter 5.

3 PROBLEM FORMULATION

In this Chapter the calibration of a manipulator with a static 2D laser scanner is presented. We start by introducing the mathematical background and formulating the system model of the manipulator kinematics and the laser measurements. The missing transformation and the calibration target will be introduced into the model heading to our proposed method. Finally we formulate an optimization problem leading to an optimal solution of the transformation between the laser scanner and the manipulator.

3.1 Background

In 3D space a rigid body transformation from frame $\mathcal{F}_a$ to $\mathcal{F}_b$ can be expressed by the homogenous transformation $\mathcal{H}_a^b \in \mathbb{R}^{4x4}$ which is a non minimal representation of the transformation $T_\tau^{b:a} \in \mathbb{R}^3 \to \mathbb{R}^3$, where $\tau = \left[\varphi, \vartheta, \psi, t_x, t_y, t_z\right]$ is the 6D vector describing the transformation. The components $\varphi, \vartheta, \psi \in [0, 2\pi[$ represent the sequential ZYX-Euler angle rotations while $t_x, t_y, t_z \in \mathbb{R}$ represent the translation along the indicated axes.

The homogenous transformation matrix $\mathcal{H}(\tau)$ representing the transformation τ is given by:

$$\mathcal{H}(\tau) =$$

$$\begin{bmatrix} c_\varphi c_\vartheta c_\psi - s_\varphi s_\psi & -c_\varphi c_\vartheta c_\psi - s_\varphi s_\psi & c_\varphi s_\vartheta & t_x \\ s_\varphi c_\vartheta c_\psi + c_\varphi s_\psi & -s_\varphi c_\vartheta s_\psi + c_\varphi c_\psi & s_\varphi s_\vartheta & t_y \\ -s_\vartheta c_\psi & s_\vartheta s_\psi & c_\vartheta & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By convention c_i and s_i substitute $cos(i)$ and $sin(i)$.

Kinematics of serial chains may be modeled as sequential homogenous transformations between the coordinate frames of the according links $\mathcal{H}_a^c = \mathcal{H}_a^b \cdot \mathcal{H}_b^c$. A 3D point in coordinate Frame $\mathcal{F}_a$ is denoted as the 4D vector $p^a = \begin{bmatrix} p_x^a & p_y^a & p_z^a & 1 \end{bmatrix}^T$, thus homogenous coordinate transformations are applicable. The manipulators configuration is defined as $c \in C$, where C describes the set of all configurations during a calibration procedure.

3.2 System Modelling

The calibration procedure aims to determine the static transformation $T_\Psi^{B:L}$ from the 2D laser scanner frame $\mathcal{F}_L$ to the frame of the manipulators base $\mathcal{F}_B$, where $\Psi = \left[\varphi, \vartheta, \psi, t_x, t_y, t_z\right]$ is the estimated 6D vector describing the transformation using the 'ZYZ' Euler convention. This transformation is expressed as the homogenous transformation matrix $\mathcal{H}_L^B(\Psi)$.

A single measurement of the 2D laser range finder represented as a 4D vector, making it applicable with the homogenous transformation, is given by ${}_t\mathcal{X}^L(i) = \begin{bmatrix} {}_tx^L(i) & {}_ty^L(i) & 0 & 1 \end{bmatrix}^T$, where $i \in \mathbb{N} | i \leq N$ is indexing the measurements, t is indexing the time and N is the amount of measurements contained in a full 360 degree laser scan. The measurement of a full 360 degree laser scan at time t is defined as the merged set

$$\mathcal{L}(t) := \bigcup_{i=1}^{N} {}_t\mathcal{X}^L(i,t)$$

The kinematic of the serial manipulator is combined as a transformation from the manipulators base frame $\mathcal{F}_B$ to the endeffectors frame $\mathcal{F}_E$ described by the homogenous transformation $\mathcal{H}_B^E$. By convention the end effectors Z-axes points towards grasping direction. The setting is illustrated in Figure 1.

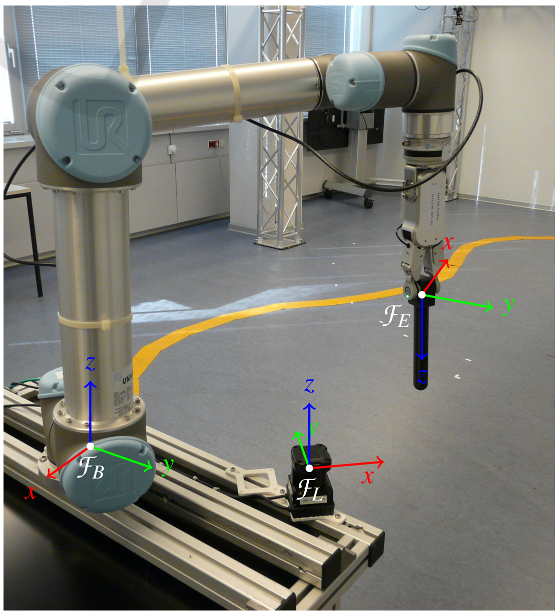


Figure 1: Setting and frame diagram of manipulator, laser scanner and end effector.

The geometry of the proposed calibration target is a cylinder with height h and diameter d. Using the assumption that the number of laser measurements $N \to \infty$ and the cylinders diameter $d \to 0$ the calibration target can be modeled as an 1D line in $\mathbb{R}^3$ pointing in Z-direction. The calibration target can now be described by the homogenous transformation

$$\mathcal{H}_{G_0}^{G_e}(\lambda) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \lambda \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

where $\lambda \in [0, h]$. The calibration target is attached to the end effector described by the homogenous transformation $\mathcal{H}_E^G$.

As the calibration target intersects the 2D laser plane a closed chain of transformations accures, illustrated in Figure 2.

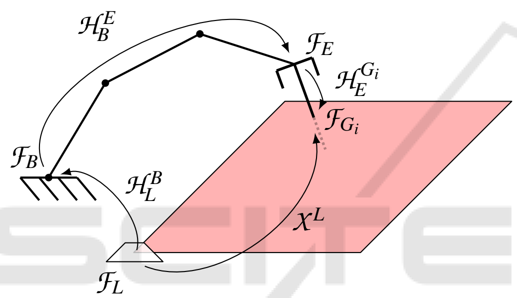


Figure 2: Illustration of setting, frame diagram and transformation chain between laser scanner, end effector, calibration target and laser-measurement.

Each configuration c of the manipulator leads to a unique intersection point in laser plane and calibration target, independent of time and measurement index. Thus the closed transformation chain is formulated as

$$\mathcal{X}^L(c) = \mathcal{H}_L^B(\Psi) \cdot \underbrace{\mathcal{H}_B^E \cdot \mathcal{H}_E^{G_0} \cdot \mathcal{H}_{G_0}^{G_i}(c,\gamma) \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix},}_{\mathcal{X}^B(c,\gamma)} \quad (1)$$

where $\mathcal{X}^L(c)$ is the subset of $\mathcal{L}$ describing the single measurement of the intersection point between laser plane and calibration tool for configuration c. $\mathcal{H}_{G_0}^{G_i}(\gamma(c))$ with $\gamma(c) \in \mathbb{R} | 0 \leq \gamma(c) \leq h$ defines the corresponding intersection point of the calibration target along its Z-axes. Thus $\mathcal{X}^B(c, \lambda)$ describes the intersection point of the calibration target and the laser plane referred to the manipulator base frame $\mathcal{F}_B$. In following Equation (1) is summarized as

$$\mathcal{X}^L(c) = \mathcal{H}_L^B(\Psi) \cdot \mathcal{X}^B(c,\gamma) \quad (2)$$

3.3 Formulation of Optimization

The main principle of the proposed calibration procedure is to measure the intersection point of the calibration target within the laser plane for various configurations of the manipulator. The closed transformation chain as expressed in Equation 2 is used to define an error depending on the missing transformation $\mathcal{H}_L^B(\Psi)$. By formulation of an optimization problem the missing transformation can now be determined optimal in terms of mean error.

As (2) describes the closed transformation chain and relates the missing transformation to the manipulator configuration and the laser measurement, an error is defined by $E = \begin{bmatrix} e_x & e_y & e_z & 0 \end{bmatrix}^T$ leading to

$$E(c,\Psi,\gamma) = \mathcal{H}_L^B(\Psi) \cdot \mathcal{X}^B(c,\gamma) - \mathcal{X}^L(c) \quad (3)$$

Note that $\gamma(c)$, describing the intersection between calibration target and laser plane, is an unknown variable, which may vary for each configuration. A scalar error describing the mean translational abbreviation between laser measurement and corresponding calibration target intersection point using transformation Ψ is given by:

$$\mathcal{E}(c,\Psi,\gamma) = \sqrt{\sum_{c \in C} E^T \cdot E}. \quad (4)$$

Finally the free optimization problem is formulated as

$$\underset{\Psi,\gamma(c)}{\text{minimize}} \quad \mathcal{E}(c,\Psi,\gamma). \quad (5)$$

Note that the solution of this optimization problem provides the parameters Ψ of the missing transformation between laser scanner and manipulater base such as $\gamma(c)$ describing the intersection points of the calibration target within the spanned laser plane for each configuration.

4 EXPERIMENTAL VALIDATION

To validate our proposed calibration procedure simulational and real experiments are performed. The simulation is used to demonstrate the feasibility of the approach under ideal conditions. The real experiment is used to evaluate the accuracy of the approach using real hardware and measurements.

4.1 Methodology

The proposed calibration procedure requires a calibration trajectory providing sufficient data for the optimization problem defined in Equation (5). As each configuration provides two independent equations and an additional unknown variable $\gamma(c)$, six configurations are needed to determine the six parameters of the transformation. Moreover the six end effector configurations should provide distinctive parameters concerning its translation in x-, y-, z-direction and orientation about x- and y-angle in ZYX-Euler convention.

The optimization problem as stated in Equation (5) is applied to the data of the simulation results and the real measurements. The Matlab implementation (*fmincon*) of a numerical interior point algorithm is used as a solver. Lower and upper bounds are defined such that

$$r_{x,y,z} \in -2 \leq r_{x,y,z} \leq 2$$
$$\varphi, \vartheta, \psi \in -2\pi \leq \varphi, \vartheta, \psi \leq 2\pi$$

The optimizer is initialised with the following parameters:

$$\Psi = \begin{bmatrix}0,0,0,0,0,0\end{bmatrix}$$

Several metrics will be used to determine the accuracy of the calibration procedure. The translational part of the transformation is evaluated using the translational abbreviation between ground truth $\widetilde{\Psi}$ and estimated transformation $\hat{\Psi}$. The rotational part is evaluated using abbreviations of ZYX-Euler angles. Both evaluations are done for the single axes such as for the associated 2-Norms:

$$e_{x,y,z} = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} = \begin{bmatrix} \widetilde{t_x} - \hat{t_x} \\ \widetilde{t_y} - \hat{t_y} \\ \widetilde{t_z} - \hat{t_z} \end{bmatrix}, \qquad e_{|xyz|} = |e_{x,y,z}|_2$$

$$e_{\varphi,\vartheta,\psi} = \begin{bmatrix} e_\varphi \\ e_\vartheta \\ e_\psi \end{bmatrix} = \begin{bmatrix} \widetilde{t_\varphi} - \hat{t_\varphi} \\ \widetilde{t_\vartheta} - \hat{t_\vartheta} \\ \widetilde{t_\psi} - \hat{t_\psi} \end{bmatrix}, \qquad e_{|\varphi\vartheta\psi|} = |e_{\varphi,\vartheta,\psi}|_2$$

The simulations are evaluated statistically, such the standard deviation σ and expected value μ of the metrics are provided.

$$\mu_i = E(|e_i|)$$
$$\sigma_i = \sigma(|e_i|)$$

4.2 Simulations

The calibration procedure as described in Chapter 3 is first validated in simulation. The aim of this evaluation is to validate the feasibility of the procedure and to determine statistically the accuracy of the provided transformation. For this purpose a transformation from laser frame to manipulator-base frame is defined and an end effector trajectory is generated for calibration. This calibration trajectory is a circular arc in x and y plane while the height and orientation was varied. In order to ensure sufficient end effector poses

Table 1: Results of simulated experiment. Circular trajectories in manipulator xy-plane. Statistical evaluation of translational and rotational error.

Translational error		Rotational error	
$\mu(e_x)/mm$	3.338	$\mu(e_{rot_x})/^\circ$	0.494
$\mu(e_y)/mm$	3.110	$\mu(e_{rot_y})/^\circ$	0.470
$\mu(e_z)/mm$	7.169	$\mu(e_{rot_z})/^\circ$	0.192
$\mu(\lvert e_{x,y,z}\rvert)/mm$	9.581	$\mu(\lvert e_{rot_{zyx}}\rvert)/^\circ$	0.800
$\sigma(e_x)/\mu m$	6.736	$\sigma(e_{rot_x})/^\circ$	0.147
$\sigma(e_y)/\mu m$	4.973	$\sigma(e_{rot_y})/^\circ$	0.108
$\sigma(e_z)/\mu m$	28.193	$\sigma(e_{rot_z})/^\circ$	0.018
$\sigma(\lvert e_{x,y,z}\rvert)/\mu m$	20.434	$\sigma(\lvert e_{rot_{zyx}}\rvert)/^\circ$	0.132

the related Euler angles are constrained, such that the z-axes intersects the laser-plane in positive direction.

The intersections between the z-axes of the end effector and the laser-plane are calculated and provide the measurements of the laser scanner. The noise of the laser scanner measurements is modelled as normal distributed using standard deviation of $\sigma_L = 10\ mm$. The noise of the manipulator is also modelled as normal distributed in x-,y-,z-direction using $\sigma_M = 1\ mm$. The ground truth of simulation is defined as $\begin{bmatrix}\widetilde{r_x} & \widetilde{r_y} & \widetilde{r_z}\end{bmatrix} = \begin{bmatrix}30 & 50 & 20\end{bmatrix} cm$ and $\begin{bmatrix}\widetilde{\varphi} & \widetilde{\vartheta} & \widetilde{\psi}\end{bmatrix} = \begin{bmatrix}5 & 7 & 3\end{bmatrix}^\circ$.

The measurements have been performed with 75 measuring points along the trajectory. The radius of the circular calibration trajectory is defined as 80 *cm*. The maximal variation of the end effectors height is 20 *cm* and the center of the circle is in the center of the manipulators coordinate frame. Figure 3 illustrates an exemlary calibration trajectory. The results are given

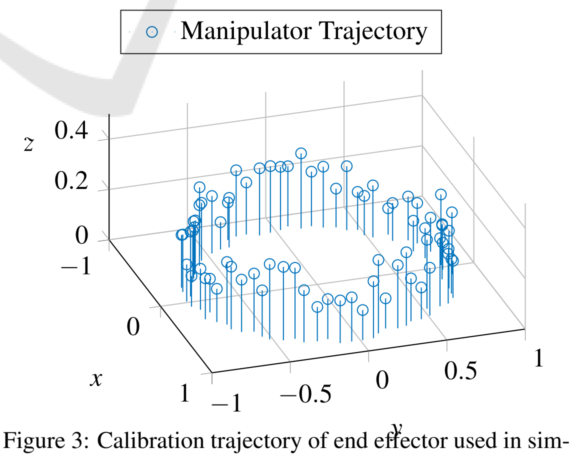


Figure 3: Calibration trajectory of end effector used in simulational experiment.

in Table 1.

Table 1 shows that the mean of the absolute translational error is about 9.5 *mm*. Furthermore a closer inspection reveals that the error along z-axis is twice the error in x- or y- direction. The rotational error about x- and y- axis is about half a degree and twice the error about z-axis. The evaluated norm of the rotational error reveals an error of 0.8°. The standard deviation of translational and rotational error show that the evaluated abbreviation between ground truth and estimated error is distributed dense about the mean values. The norm of the mean translational error 9.5 *mm* is below the laser measurements standard deviation of 10 *mm*.

4.3 Real Experiments

The proposed method has also been evaluated in a physical environment using real measurements of a laser scanner and manipulator.

The deployed laser scanner is the Hokuyo model UTM-30LX-EW and the manipulator that was used for experimental evaluation is the Universal Robot UR5. The technical details related to the accuracy of the measurements are as follows: The repeatability of the UR5 manipulator is ± 0.1 *mm*. The accuracy of the Hokuyo UTM-30LX-EW laser scanner is ± 30 *mm*

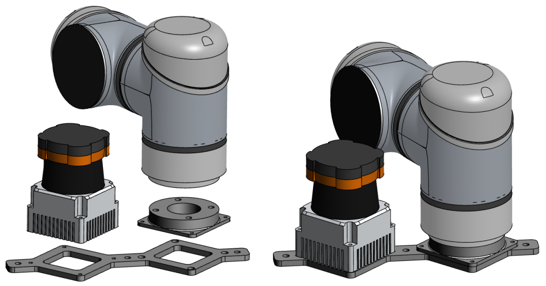
The ground truth of the real experiments has been determined by generating a closed transformation chain between manipulator and laser scanner frame considering the provided CAD data of the laser scanner.

The transformation from manipulator base to end-effector is known. The laser scanner is assembled on a self developed calibration mount. An Attachment for the manipulator, that fits exactly into the mount, is used, to constrain a known transformation between end effector and laser scanner frame. The known transformations from this serial chain deliver the unknown transformation between manipulator base and laser scanner.

Figure 4 shows the developed calibration system. The known technical dimensions of the laser scanner and the developed sensor mount provide a transformation accuracy of ground truth in the range of manufacturing tolerance which is ± 0.2 *mm* for the used 3D-printer.

As the physical calibration target is a 3D body and provides multiple scan points describing its intersection with the laser plane, the laser scan needs to be processed before optimization in real experiments. As the formulated model assumes a single intersection point of a 1D line, the center of the intersecting calibration tool is required.

The intersection of the cylinder shaped calibration tool and the laser plane is assumed to be an ideal circular arc. As the laser scanner only perceives a semicircle, the center is determined by calculating the arithmetic mean of the measurements and correcting it about $R \cdot \pi/4$. Figure 5 illustrates the correction of the laser measurements.



(a) Disassembled calibration system (b) Assembled calibration system

Figure 4: Calibration system providing ground truth. Laser-scanner mount and manipulator attachment

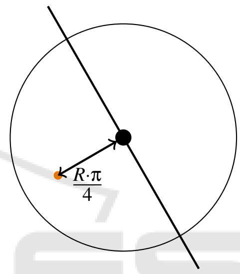


Figure 5: Correction of laser measurements to determine the center of the circular intersection. The orange dot marks the arithmetic mean value of the semicircle. The black dot marks the center of the circle.

The calibration trajectory is illustrated in Figure 6. The manipulator moves the end effector in two semi-circles with different radii and heights. The position is held for 3 seconds in 20 degree intervals along the semi-circles. The orientation of the end effector was varied for each interval. Evaluations are given in Table 2. The experimental setting is illustrated in Figure 1.

Table 2: Results of real experiment. Circular trajectorie in manipulator xy-plane. Evaluation of translational and rotational error.

Translational error		Rotational error	
e_x/mm	11.809	$e_{rot_x}/°$	2.011
e_y/mm	4.267	$e_{rot_y}/°$	0.454
e_z/mm	2.346	$e_{rot_z}/°$	0.219
$e_{\|xyz\|}/mm$	12.559	$e_{\|rot\|}/°$	2.073

The absolute translational and rotational error is about 12.6 *mm* and 2.1°. A qualitative inspection reveals that the translational error in x-direction is almost three times the absolute error in y- and more than five times the translational error in z-direction. The

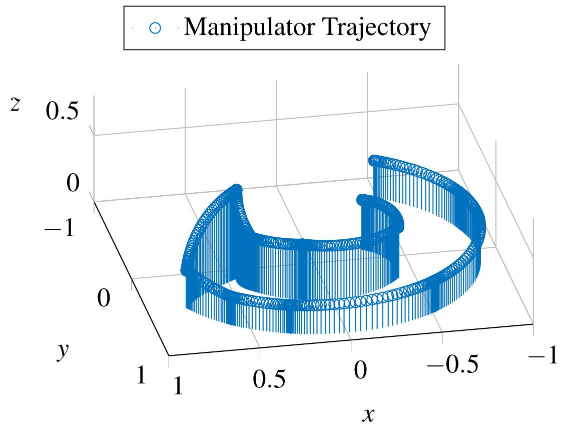


Figure 6: Calibration trajectory of end effector used in real experiment.

same relations occur for the rotational error. The rotational error about the normal axis of the laser plane is minimal while the rotational error around the X-axis is maximal.

As the calibration trajectory for the real measurements cannot cover the whole area of the laser scanner because of the limited measuring range of 270°, this explains the relatively large error about the X-axis. The data of the measurement cannot cover the whole space and overweights the data in x-direction in optimization.

However, the evaluated abbreviation between ground truth and estimated translation has to be relativized, as the used laser scanner provides an accuracy of $\pm 30\ mm$. The provided calibration procedure obtained a translational error which is less than a half of this accuracy. Moreover the rotational error of about $2.1°$ is mostly influenced by the rotational error around the X-axis. As the laser measurements only occur in x- and y-plane, this rotational error has almost no effect on the measurements in x- and y-direction. A rotational error around the X-axis of $2.1\,°$ leads to a minimal translational error along the X-axis as $cos(2.1°) = 0.9994$. Under the assumption that the laser measurements shall be used for manipulation the range of the manipulator shall not be larger than $800\ cm$ leading to a translational error of $0.48\ mm$.

5 CONCLUSIONS

In this paper we present a new calibration procedure to determine the transformation between a manipulators' base and a 2D laser scanner. The proposed calibration procedure does not require additional sensors or complex calibration targets. Instead merely a simple 1D calibration target is required. The transformation is determined by solving an optimization problem that fits the missing transformation into the closed transformation chain between manipulator pose and laser measurement.

The approach has been evaluated by simulation and physical experiments using a Universal Robot UR5 manipulator and real laser measurements of a Hokuyo UTM-30LX-EW laser scanner.

The results show that the accuracy of the calibration procedure is within the range of the laser scanners accuracy. The simulational results as well as the results of the real experiments show variations between the evaluated translational and rotational errors along and around the several axis. While the pose of the end effector provides 6D data, the measurements of the laser scanner only reveal 2D data. Any kind of calibration procedure has to resolve the problem of fitting a 2D plane by projection from 6 dimesional space into 2D space. This fundamental type of problem may be the reason why the rotational and translational error about and around the several axis vary after optimization.

Future research may focus on varying the calibration target. The radius of the physical calibration target may influence the calibration as the center of the intersection may be determined more precisely. A longer calibration target could also improve the calibratin error as it enables a higher variation of feasible trajectories. The influence of different trajectories is also a point of interest for future research.

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