# RoboTSP – A Fast Solution to the Robotic Task Sequencing Problem

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***Abstract*—**

## I. Introduction

Robots have been used in many industrial applications, such as pick and place, spray-painting, and spot-welding. In those applications, the robots either do not need very high accuracy (such as in material handling for large objects), or the robots are programmed online (programming by teaching), where the important parameter is the repeatability of the robot, not the accuracy. Repeatability refers to the capability of the robot to return to the same location as previously taught accurately, whereas accuracy refers to the capability of the robot to achieve a location (computed based on the robot kinematics model) in the robot workspace. If the robots are taught by teaching pendants to reach certain locations, the accuracy of the robot becomes irrelevant to the task.

However, there are a lot of interests to use robot on many other applications where the accuracy of the robot becomes very crucial, where the robot has to adapt to each task automatically with a great precision. Take, for example, a robot drilling task. In robot drilling task, the robot is supposed to drill several holes at precisely-defined locations on a workpiece, which can change for each task. We can teach the robot the position of the holes manually for each workpiece, but that will take a lot of time and effort. If we want to program the robot offline for such a task, the robot has to be able to do a few things: the robot has to "look" at the workpiece, determine the location of the holes, and finally move to that location. The accuracy of such a robotic system depends on several factors: The accuracy of the robot arm, the accuracy of the measurement system, and the accuracy of the end effector tool.

The accuracy of the robot arm is determined by how closely the kinematic parameters of the robot model resembles the actual kinematic parameter of the physical robot. This is affected by the manufacturing process, the assembly process, and the wear and tear during the operation of the robot. To achieve a better accuracy, a robot calibration is normally conducted, either by using an external measurement system (such as motion capture system, or spinarm, or CMM), or by constraining the motion of the end effector.

The accuracy of the measurement system can be divided into two parts: the accuracy of the measurement device itself, and the accuracy of the transformation between the measurement frame to the robot frame (often called the extrinsic parameters). A camera system, for example, is generallly less precise as compared to a laser system, although a camera can give more information. To obtain accurate transformation from the measurement coordinate to the robot coordinate, the information from the CAD model is not sufficient, as there will be error during the assembly, and very often the measurement coordinate is located inside the measurement device, causing it to be difficult to be measured accurately. A process known as hand-eye calibration is normally used to find such transformation.

Lastly, the accuracy of the end effector transformation. This is the transformation from the robot flange to a predetermined location on the end effector (such as the tip of the drilling bit). Calibration of the end effector is generally known as TCP calibration.

In this paper we concern ourselves with solving the first two issues. We propose to use a near-range 2D laser range finder, attached on a robot arm, to calibrate the kinematics parameters of the robot while at the same time also calibrating the extrinsic parameters of the LRF. The 2D LRF is chosen because it can give very accurate measurement data, both for the calibration and for the subsequent task (such as drilling).

The overall procedure is as follows: 1. The scanner is attached on the robot, and three (approximately) perpendicular planes are set around the robot. The location (position and orientation) of the planes only needs to be known approximately. 2. The robot is moved to several positions, such that the laser range finder's plane intersects each of the plane (one at a time). The data from the laser as well as the joint angles information are collected. 3. An optimization algorithm (Levenberg-Marqueadt) is used to find the optimal robot kinematics parameters, together with the LRF extrinsic parameters, with the following constraints: the projected LRF data should lie on the three planes.

The proposal has several advantages: 1. It does not require an external measurement system. The measurement device that we used to calibrate the robot is also the device that will be used on the actual process. 2. It does not require specially calibrated object to calibrate the robot. The planes coordinates do not need to be known precisely, only approximately. 3. The calibration can be performed through the whole robot workspace, not only a local portion of it.

## II. Related works

### A. Calibration of robot kinematic parameters

Robot kinematics calibration have been researched for quite a long time, some of the earliest work began in 1980s. Generally, the calibration process can be divided into unconstrained and constrained calibration. In unconstrained

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calibration, the robot moves its end-effectors to several poses freely, while an external measurement system measures the pose. The measured pose is then compared to the one computed from the kinematics model, and the model can be updated to minimized the difference between the model and the actual pose. For example, Ginani and Mota [1] calibrate an ABB IRB 2000 industrial robot using a ROMER measurement arm, which improves the mean/maximum position errors from 1.25mm/2.20mm to 0.30mm/1.40mm. Ye et al. [2] used a Faro laser tracker to calibrate an ABB IRB 2400/L, and improve the mean/maximum position errors from 0.963mm/1.764mm to 0.470 mm/0.640mm. In [3], Nubiola and Bonev used a Faro laser tracker ION to calibrate an ABB IRB 1600-6/1.45 robot. The mean/maximum position errors are reduced from 0.968mm/2.158mm to 0.364 mm/0.696 mm, respectively.

The issue with such calibration process is the expensive cost of the external measurement system. For example, the cost of a laser tracker is more than $100,000$[3]. Therefore, many researchers try to find calibration methods which only rely on the internal sensors of the robot, and by constraining the motion of the end-effector to provide the calibration equations. In [4], Ikits and Hollerbach propose a kinematic calibration method using a planar constraint. The robot end effector (a touch probe) is moved to touch random points on a plane. When the touch probe is in contact with the plane, the joint angles are recorded. The kinematics parameters of the robot model are then updated to satisfy the planar constraint. In [5], Zhuang et al. investigated robot calibration with planar constraints, in particular the observability conditions for the parameters of the robot kinematic model. They proved that a single-plane constraint is insufficient for calibrating a robot,and a minimum of three-plane constraint is necessary. Using a three-plane constraint, the constraint system is proved to be equivalent to an unconstrained point-measurement system under three conditions: a) All three planes are mutually non-parallel, b) The identification Jacobian of the unconstrained system is nonsingular, and c) Measured points from each individual plane do not lie on a line on that plane. They verified the theory by doing a simulation on a PUMA560 robot. In [6], Joubair and Bonev calibrated both the kinematic and non-kinematic (stiffness) parameters of a FANUC LR Mate 200iC industrial robot by using planar constraints, in the form of a high precision 9-in. granite cube. The robot is equipped with an MP250 Renishaw touch probe, which is then moved to touch four planes of the granite cube. The granite cube's face is flat to within 0.002mm. They improved the maximum plane error from 3.740mm to 0.083mm.

### B. *Calibration of extrinsic 2D laser range finder parameters*

Extrinsic calibration of a laser scanner consists of finding the correct homogeneous transformation from the laser coordinate frame to the robot coordinate frame. While it is similar to hand-eye calibration of a robot-camera system, the data obtained from a laser is less than a camera, which makes it slightly more difficult. A camera on a robot is normally calibrated by using a checkerboard pattern, the pose of which (position and orientation) with respect to the camera can be obtained by the camera using just a single image. In contrast, we cannot obtain the pose of an object easily using just a single data from a laser scanner.

Most of the works on extrinsic calibration of LRF involves a camera, since both sensors are often used together in many applications. The works are mostly based on Zhang and Pless work[7]. They proposed a method to calibrate both a camera and a laser range finder using a planar checkerboard pattern. First, the camera is calibrated by using a checkerboard pattern, using a standard hand-eye calibration. The calibrated camera is then used to calculate the pose of the pattern. Next, the robot is moved to several poses with the LRT pointing to the pattern. By using the geometric constraints that all the data points from the laser should fall on the pattern plane, the extrinsic parameters of the LRF can be obtained. Finally, the same constraints is used to optimize both the intrinsic and extrinsic parameter of the camera and the extrinsic parameter of the LRF. The nonlinear optimization problem is solved with the Levenberg-Marquardt method. Unnikrishnan and Hebert [8] used the same setup as [7], although they do not optimize the camera parameter simultaneously due to the nonlinearity of the resulting cost function. Li et al. [9] used a specially designed checkerboard to calibrate the extrinsic parameters between a camera and a LRF, and claim that the result is better than [7]. Vasconcelos et al. [10] developed a minimal closed-form solution for the extrinsic calibration of a camera and a LRF, based on the work in [7].

Our proposed algorithm can be seen as a combination of the algorithm for extrinsic calibration of LRF [7] and the algorithm for calibration of the robot kinematics parameter using three planar constraints [5]. The proposed method simultaneously optimize the LRF extrinsic parameters and the robot kinematics parameters to satisfy the planar constraints. It has the following advantages: 1. Unlike [7], the method does not need an additional camera to calibrate the LRF 2. The method does not need another expensive external measurement system. The measurement is done using the LRF, which will also be used in the robot task, so it does not incur additional cost. Moveover, LRF can achieve very high accuracy at much lower cost, as compared to measurement system such as Vicon or Faro Laser Tracker. 3. Unlike [5], it does not need a precisely manufactured calibration object such as the granite cube, whose planes location and orientation are supposed to be known accurately. The method only requires three flat surfaces, which are oriented somewhat perpendicularly, and the location and orientation are known only approximately. 4. The calibration setup can be done very easily, since the planes do not need to assume precisely known locations.

## III. Method

The calibration setup is depicted in figure ***, where three perpendicular planes are installed around the robot. A laser range finder is attached on the robot flange. For each plane, the robot is moved to $N$ poses such that the laser line falls on the respective plane. The joint angles of the robot and the data from the LRF are then recorded for the calibration.

This section provides the detail on how to calibrate both the extrinsic parameters of the LRF and the robot kinematics parameters. First, the initial estimate of the LRF extrinsic parameter is obtained by using linear least-square method. After that, the LRF extrinsic parameters and the robot kinematics parameters are optimized by using nonlinear optimization method. Finally, SVD is used to identify which parameters are identifiable, and the steps to handle the unidentifiable parameters are then presented.

### A. Obtaining Initial Estimate of the LRF Extrinsic Parameters

### B. Optimizing LRF Extrinsic Parameters and Robot Kinematic Parameters

### C. The identifiability of the optimization parameters

### D. Handling the unidentifiable parameters

## IV. Conclusions

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