Calibration of Industrial Robots by Magnifying Errors on a Distant Plane


Abstract—This paper describes a robot calibration approach called the virtual closed kinematic chain (ViCKi) method. Traditionally, calibration requires the measurement of the position and orientation of the end effector, and measurement resolution limits the accuracy of the robot model. In ViCKi, we attach a laser to the end effector to create a virtual 7th link. The laser spot produced on a distant plane, the end of this virtual link, magnifies small changes at the end effector, resulting in a high resolution error measurement of the end effector. The accuracy of the robot after using the proposed calibration procedure is measured by aiming at an arbitrary fixed point and measuring the mean and standard deviation of the radius of spread of the projected points. The mean and standard deviation of the radius of spread were improved from 5.64mm and 1.89mm to 1.05mm and 0.587mm respectively. It is also shown in simulation that the method can be automated by a feedback system that can be implemented in real-time.

I. INTRODUCTION

It is well known that industrial robots are highly repeatable but not very accurate. Since most industrial applications are programmed by teach pendant to produce a sequence of points, replay of these points relies strictly on repeatability; accuracy simply does not matter. The majority of robotic applications that capitalize on repeatability, e.g., pick and place, spray painting, have already been done. For more advanced applications, such as sensor-based assembly, accuracy plays a significant role.

The position and orientation of a robot is usually determined using forward kinematics with Denavit-Hartenberg (DH) parameters for each link of the robot. Robot accuracy ultimately depends on the accuracy of the DH parameters. Some variation comes from machining inaccuracies and others from assembly process. Most manufacturers of robots do not focus on accuracy because, if accuracy is achieved by higher tolerance in machining, the cost of the robot increases dramatically, adversely affecting a company’s sales potential. Hence a software calibration approach to identify the DH parameter values is needed to advance the state of the art in robotics. After a calibration procedure in the robot factory, each robot controller can be updated, e.g., by writing non-volatile memory with the correct robot-specific DH parameter values instead of the standard design values. Alternatively, for applications with higher accuracy demands like sensor-based assembly, robotic surgery, etc., the more accurate DH parameters can be used to compute a more accurate numerical inverse kinematics. This paper describes a DH parameter calibration approach that fits this need.

II. RELATED WORK

There has been considerable research in the field of robotic calibration. A brief review is presented in [1-3]. Existing techniques can be classified into open-loop and closed-loop approaches. Open-loop methods involve measuring the end-effector pose which require special equipment (such as theodolites, inclinometers, ball-bar, and coordinate measuring machines [4]). The process of obtaining these measurements is time consuming and must be repeated for high precision systems. The resolution of measurements near the end-effector is limited by the equipment used.

Closed-loop methods [5-8], on the other hand, use the joint angle measurements already in the robot, and thereby can be considered self-calibrating. These methods impose some constraints on the end-effector and the joint readings alone are used to calibrate the robot using kinematic closed-loop equations. Some researchers in the past have used linear constraints on the end-effector positions allowing the end-effector to slide along a line, e.g., Newman et al. [5] used a laser line. Zhuang et al. [6] imposed plane constraints on the end-effector positions. Using a plane constraint is problematic because it is difficult to be certain that the end-effector is exactly on the surface; neither above it nor indenting it.

Bennet et al. [7] considered manipulators as mobile closed kinematic chains. It is difficult to move a physically closed kinematic chain from one position to another while maintaining the physical constraints. Hence it is difficult to gather accurate joint readings. Meggiolaro et al. [8] used a single endpoint contact constraint, equivalent to a ball joint, to calibrate the robot. The robot moves to different configurations that satisfy the contact constraint. This method needs a physical contact point, and suffers from the
same problems as the plane constraint methods.
A new method called “virtual closed kinematic chain” (ViCKi) is proposed herein. Unlike previous closed-loop methods, this approach does not require any physical constraints.

III. STAUBLI MODEL AND PARAMETERS

A. Workcell

The workcell consists of a Staubli RX-130, shown in Fig. 1, which is mounted on a robot transport unit (RTU) that moves the robot along a track. This robot has six rotary degrees of freedom.

A laser pointer tool (with adjustable pivot) is attached to the robot wrist. The laser tool’s pivot is adjusted to align its orientation roughly with the Z-axis of the end-effector and fixed rigidly. This misalignment is also modeled in the proposed calibration procedure. The robot can aim the laser tool at some location.

B. Staubli Coordinate systems

A model of the robot is built with coordinate system definitions according to Craig’s modified Denavit-Hartenberg (DH) [9, 10] and Hayati (HR) [11] conventions combined as shown in Fig. 2.

We use notation C012 for cos(θ1+ θ2), S012 for sin(θ1+ θ2) and ATB for transformation matrix which transforms points described in frame B to points in frame A. The transformation matrices from frame ‘i-1’ to frame ‘i’ with DH parameters (αi, ai, θi and βi) is given by

\[ T_i = R_i(\alpha_i)T_{i}(a_i)R_{i}(\beta_i)T_{i}(\theta_i) \tag{1} \]

\[ \begin{bmatrix}
    C_{\theta_{i}} & -S_{\theta_{i}} & 0 & a_i \\
    S_{\theta_{i}}C_{\beta_{i}} & C_{\theta_{i}}C_{\beta_{i}} & -S_{\theta_{i}} & -a_i \\
    S_{\theta_{i}}S_{\beta_{i}} & C_{\theta_{i}}S_{\beta_{i}} & C_{\theta_{i}} & d_i \\
    0 & 0 & 0 & 1
\end{bmatrix} \]

where \( \alpha_i \) is the angle between \( Z_{i-1} \) and \( Z_i \) measured about \( X_i \), and \( a_i \) is the distance between \( Z_{i-1} \) and \( Z_i \) measured along \( X_i \), \( \theta_i \) is the angle between \( X_{i-1} \) and \( X_i \) measured about \( Z_i \), and \( \beta_i \) is the angle of rotation about \( Y_i \) axis.

The distance between \( X_{i-1} \) and \( X_i \) measured along \( Z_i \) is set to a fixed value for this transformation.

The transformation matrices from frame ‘1-1’ to frame ‘1’ with Hayati parameters (\( a_1 \), \( a_1 \), \( \theta_1 \) and \( \beta_1 \)) is given by

\[ T_1 = R_1(\alpha_1)T_{1}(a_1)R_{1}(\beta_1)T_{1}(\theta_1) \tag{2} \]

\[ i-i \]

\[ \begin{bmatrix}
    C_{\theta_{1}} & -S_{\theta_{1}} & 0 & a_1 \\
    S_{\theta_{1}}C_{\beta_{1}} & C_{\theta_{1}}C_{\beta_{1}} & -S_{\theta_{1}} & -a_1 \\
    S_{\theta_{1}}S_{\beta_{1}} & C_{\theta_{1}}S_{\beta_{1}} & C_{\theta_{1}} & d_1 \\
    0 & 0 & 0 & 1
\end{bmatrix} \]

where \( a_1 \) is the angle between \( Z_{1-1} \) and \( Z_1 \) measured about \( X_1 \), and \( a_1 \) is the distance between \( Z_{1-1} \) and \( Z_1 \) measured along \( X_1 \), \( \beta_1 \) is the angle of rotation about \( Y_1 \) axis.

The transformation matrices from frame ‘1-1’ to frame ‘1’ with DH parameters (\( a_1 \), \( a_1 \), \( \theta_1 \) and \( \beta_1 \)) is given by

\[ T_1 = R_1(\alpha_1)T_{1}(a_1)R_{1}(\beta_1)T_{1}(\theta_1) \tag{2} \]

\[ i-i \]

\[ \begin{bmatrix}
    C_{\theta_{1}} & -S_{\theta_{1}} & 0 & a_1 \\
    S_{\theta_{1}}C_{\beta_{1}} & C_{\theta_{1}}C_{\beta_{1}} & -S_{\theta_{1}} & -a_1 \\
    S_{\theta_{1}}S_{\beta_{1}} & C_{\theta_{1}}S_{\beta_{1}} & C_{\theta_{1}} & d_1 \\
    0 & 0 & 0 & 1
\end{bmatrix} \]

where \( a_1 \) is the angle between \( Z_{1-1} \) and \( Z_1 \) measured about \( X_1 \), and \( a_1 \) is the distance between \( Z_{1-1} \) and \( Z_1 \) measured along \( X_1 \), \( \theta_1 \) is the angle between \( X_{1-1} \) and \( X_1 \) measured about \( Z_1 \), and \( \beta_1 \) is the angle of rotation about \( Y_1 \) axis.

It is well known that the DH parameters have a singularity when neighboring joint axes are parallel. For the Staubli robot, joints 2 and 3 are parallel. Consequently, we use HR for this transformation and DH for all other transformations. Since the base coordinate frame ‘0’ is arbitrary, it is chosen to coincide with the frame ‘1’ when the reading of joint 1 is zero. The coordinate system of the end-effector (frame 6) is also arbitrary. It is chosen such that the X-axis of this frame coincides with X-axis of frame 5 when the joint 6 reading is 180°. Also, for the Staubli RX-130, \( d_6 \) is set to a fixed value.
of 110mm.

Table I lists the DH/HR parameters of the complete robot model. Either ‘d’ or ‘β’ is used for the fourth parameter depending on whether the transformation is DH or HR. The parameter that does not apply in each row is marked as ‘--’. The ‘θ’ listed in the table are the joint offsets. These offsets are added to the actual readings of the joints to compute the transformation matrices.

C. Laser Coordinate Systems

The laser tool is not perfectly aligned with the z-axis of the end effector (Z6) and the misalignment needs to be modeled by a transformation matrix. A coordinate system (O7X7Y7Z7) is chosen for the laser tool such that the Z-axis coincides with the laser line. Both the orientation of x-y axes and the origin along the laser line are arbitrary. Four independent parameters are required to describe a line (laser) in 3D space. Since the laser Z-axis (Z7) is closely aligned with the robot end effector Z-axis (Z6) we choose the four required parameters as, two rotations about X and Y (these angles of rotations are close to zeros) and two coordinates of translation in X-Y plane (also close to zeros).

We choose the X-Y axis and the origin of laser coordinate system to coincide with the previous coordinate system when the four parameters are zeros. The transformation matrix is given by

\[
T = R_x(\theta_x)R_y(\theta_y)T_x(p_x)T_y(p_y)
\]

computed by Eq. (3).

\[
\begin{bmatrix}
C\theta_y & 0 & S\theta_y & p_xC\theta_y \\
S\theta_yC\theta_x & C\theta_x & -S\theta_xC\theta_y & p_xS\theta_xS\theta_y + p_yC\theta_x \\
-C\theta_yS\theta_x & S\theta_x & C\theta_xC\theta_y & -p_xC\theta_xS\theta_y + p_yS\theta_x \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

This can be written as

\[
\begin{bmatrix}
C\theta_y & 0 & S\theta_y & p_xC\theta_y \\
S\theta_yC\theta_x & C\theta_x & -S\theta_xC\theta_y & p_xS\theta_xS\theta_y + p_yC\theta_x \\
-C\theta_yS\theta_x & S\theta_x & C\theta_xC\theta_y & -p_xC\theta_xS\theta_y + p_yS\theta_x \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Therefore, the total number of independent calibration parameters is 24 – 4 (fixed base) - 2(fixed end effector) + 4(laser) = 22.

IV. VIRTUAL CLOSED-LOOP KINEMATIC CHAIN CALIBRATION

A new method called ViCKi, “virtual closed kinematic chain method,” is developed to calibrate the robot. This method falls under the class of closed-loop methods where only joint readings are used to calibrate the robot. A laser tool is attached to the end-effector of the robot. The laser tool on the robot acts as a virtual telescopic (prismatic) link giving the robot 7 DOF, the seventh joint being the length of the laser line from the end effector to the projected laser point on an object. Thus aiming the laser pointer at a fixed point (on a plane or some object) creates a virtual closed kinematic chain.

The calibration is performed by aiming the laser pointer at an arbitrary but fixed point P on an object (usually a plane), adjusting the joint values to maintain the laser on point P using various joint values. This effectively becomes the single end point constraint for the 7 DOF system. The coordinates of the fixed point P in robot’s base frame are unknown and must be included in the calibration model’s parameters. Since the coordinates of the fixed point (P) are also included in the parameters to be determined, the scale factor of the model is indeterminate. To overcome this problem we need a second fixed point relative to the first fixed point. This can be accomplished in two ways.

1) A second fixed point is chosen such that the distance between the two fixed points is known (D) and the two parameters for the direction are included in the calibration model as shown in Fig. 3. This can usually be achieved through a calibration plane.

2) The same fixed point is used but the base of the robot is purely translated by known distance (D) and the two parameters for the unknown translation direction are
In our case, since we have a RTU (robot transport unit) which can translate the robot along the rail by a known distance, we use the second alternative. The laser tool is aimed at the fixed point from various positions. The parameters of the model are determined by minimizing the sum of the normalized shortest distance of the fixed point from all the laser lines. Since the shortest distance error depends on the distance of the object plane from the end effector (i.e., length of the laser line), it is normalized by the length of the laser line.

We denote the 22 parameter set for the robot and laser tool as $\Phi_{RL}$. The three parameter set for the 3D point are denoted as $\Phi_{3D}$ and the two parameters for the direction of translation as $\Phi_i$ and $\Phi_m$. We have two sets of joint configurations, one for each fixed point (or one for each base position). We use the notation $^i\mathcal{I}_j$ for joint set $1$, $^i\mathcal{I}_j$ reading. For each joint configuration in first set transformation matrix from base to laser frame $^1\mathcal{I}_j\left(\Phi_{RL} \ ^1\mathcal{I}_j\right)$ is computed which gives the position $^1\mathcal{I}_j\left(\Phi_{RL} \ ^1\mathcal{I}_j\right)$ and the direction of the Z-axis $^1\mathcal{I}_j\left(\Phi_{RL} \ ^1\mathcal{I}_j\right)$ of the laser line in columns 4 and 3, respectively, of the transformation matrix. The shortest distance of the 3D point $\Phi_{3D}$ from the laser line is determined and normalized with the length of the laser line. This is the error, i.e., the cost function $^1\mathcal{I}_j\left(\Phi_{RL} \ ^1\mathcal{I}_j \ ^1\mathcal{I}_j\right)$ for this joint configuration. For the second set the error $^2\mathcal{I}_j\left(\Phi_{RL} \ ^2\mathcal{I}_j \ ^2\mathcal{I}_j\right)$ is computed with the 3D point

$$\Phi_{3D}=\Phi_{3D}+\begin{pmatrix}
\cos(\Phi_i) \cos(\Phi_m) \\
\sin(\Phi_i) \cos(\Phi_m) \\
-\sin(\Phi_m)
\end{pmatrix} \cdot D \tag{4}$$

where $\Phi_i$ and $\Phi_m$ are the angles of rotation about $z$ and then $y$ to align the $x$-axis along the unknown translation and $D$ is the known length of the translation. Since the direction of translation in our present case is almost aligned along the $x$-axis of our robot the initial guess for all rotation parameters is zero. The complete parameter set $\Phi=[\Phi_{RL} \ \Phi_{3D} \ \Phi_i \ \Phi_m]$ is determined by minimizing the total sum of the squares error.

$$\Phi_{min}=\text{MIN} \left(\sum_{i=1}^{N} E_i^2 + \sum_{i=1}^{N} E_i^2 \right) \tag{5}$$

where $\Phi_{min}$ is the required parameter set obtained by minimizing the total sum of squares of errors and $N$ is the number of readings in each set. We have a MATLAB minimization routine to compute the values of the parameters. The user is referred to [12] for description of the minimization problem.

A. Feedback system and stability

The calibration procedure requires many different robot joint configurations that aim the laser tool at the particular point on a distant object. This process can be time consuming if a teach pendant is used. Instead we use inverse kinematics with approximate parameters and 3D coordinates to compute various joint configurations that aim at the fixed point and adjust them using a feedback system. The feedback system automatically redirects the laser spot on a plane to a desired location. The data acquisition process is thus accelerated.

A model of the robot and laser tool is constructed in Simulink. The errors in aiming the laser at a fixed point due to errors in parameters are within ±10mm, which are well within the limits of the feedback system that can correct errors of ±500mm away from the desired point. The feedback system uses the initial parameters and approximate position and orientation of the camera system to compute the inverse Jacobian. The system appears very stable since the direction of motion of each joint to move the desired laser point is not sensitive to the small differences in the robot calibration parameters. We have constructed two different feedback systems. The first one uses position control and the second one uses a PID (position, integral and differential) control as shown in Fig. 5. The gains and parameters for the PID feedback system are chosen to make the system stable.

Using this approach, the calibration procedure can be automated in industry. A camera detects the laser point and is used as feedback to change the robot joint angles so as to move the laser point to the desired point $P$.

B. Procedure

The procedure is summarized in these steps

1) A very large set (M) of random joint configurations within the required ranges is generated.

2) Using the approximate parameter values of the robot,
laser and the 3D point a subset (N) of joint configurations is selected that aim the laser tool close to the 3D point.

3) The robot is moved to one of the N locations in the joint configuration set and the joint values are adjusted to
aim the laser point at the constant location. This accurate joint configuration is stored.

4) Step 3 is repeated for all of the N joint configurations.

5) Move the Robot on the RTU by a known distance
D=1000mm (or use a second fixed point at a known distance
from first).

6) Repeat the steps 1 through 4 by aiming at the same
location used previously (or aim at the second fixed point).

7) Using these data and a nonlinear minimization routine,
compute the parameter values.

V. ANALYSIS OF ViCKI

A. Magnification of observation error

The main advantage of the proposed method is that the
distant laser point is very sensitive to the joint values, i.e., it
magnifies the error (a very fine adjustment in the joint angle
configuration is needed to aim at a particular point), which
facilitates acquiring more accurate joint values for the
calibration. The ‘Observation plane’ is an arbitrary plane
(any arbitrary orientation facing the robot base) passing
through the 3D point on which the laser is aimed and can be
adjusted to coincide with the point. It should be noted that
this observation plane can be chosen arbitrarily passing
through the 3D fixed point; the only effect will be a change
in the Jacobian used in feedback. Hence without loss of
generality assume the observation plane is parallel to X-Z
and at a distance “β” that is Y=β is the equation of the plane.

Let the transformation matrix of the laser pointer with
respect to the base of the robot be

\[ T = \begin{bmatrix}
R_{11} & R_{12} & R_{13} & O_x \\
R_{21} & R_{22} & R_{23} & O_y \\
R_{31} & R_{32} & R_{33} & O_z \\
0 & 0 & 0 & 1
\end{bmatrix} \tag{6} \]

We know that \( O= (O_x, O_y, O_z)^T \) is the origin of the laser
coordinate system and \( Z=(R_{13}, R_{23}, R_{33})^T \) is the Z-axis,
which is coincidence with the laser line. Any general point
on this line (i.e., on the laser line) is \( P=O+λZ \). The laser is
aimed at the observation plane (whose equation is \( Y=β \))
hence the aimed point (P) lies on the observation plane and
its solution is

\[ P_y=β \Rightarrow O_y+λR_{23}=β \Rightarrow λ=\frac{(β-O_y)}{R_{23}} \tag{7} \]

Using (7) we can compute the location of the laser point
on the observation plane in its planar 2D coordinates (x-z in
the present case), which is given by

\[ \{K_x, K_z\}^T = \begin{bmatrix}
O_x+βR_{13} \\
O_z+βR_{23}
\end{bmatrix} \tag{8} \]

Since we choose β to be large, the change in the 2D point
of projection is magnified as compared to just the change in
the position and/or orientation of the end effector. (β-O_y)
is the distance between the end-effector or TCF (Tool Control
frame) and the plane. \( R_{13}/R_{23} \) and \( R_{23}/R_{23} \) are the tangents
of the angles of the laser line with the Y- axis.

Fig. 6 shows the variations of the positions of the TCF
and the laser point on planes at β=3000 mm and β=5000 mm
with variations in joint 1 angle. It can be inferred from the
plot that to have same error (0.1mm) in measurements of
either TCF or laser position (on plane β=5000 mm), the
errors in joint 1 angle are 0.01deg and 0.001deg respectively, i.e. for laser point case it is 10 times lower than
the TCF case. Consequently, if the error associated with
aiming the laser point at the desired point that is 5000mm
away is less than 0.1mm, the error associated with joint 1
will be less than 0.001deg. The variations in laser point and
TCF are in the same order of magnitude with variations in
other joint angles. Thus this method is more accurate in
obtaining the joint configuration data when compared to any
method that uses the TCF position or orientation measurements.

B. Optimum distance for observations

The magnification of error as discussed in previous
section is directly dependent on the distance (β) of the
observation plane from base of the robot. The uncertainty in
aiming the laser (due to limited resolution of the joints) also
increases with β.

The uncertainty in origin of laser line (ΔO) and laser
angle (Δθ) are given by
\[ ΔO = O_m + O_s \] and \[ Δθ = θ_m + θ_s \] respectively
where \( O_m \) and \( O_s \) are mean and standard
deviation of errors in origin of laser, and \( θ_m \) and \( θ_s \) are the
mean and standard deviation of errors in direction of laser
due to limited resolution of joints. The uncertainty in aiming
laser ($\Delta l$) at a distance $\lambda$ is given by $\Delta l = \Delta O \pm \lambda \sin(\Delta \theta)$.

Let $\Delta P$ be the uncertainty in observations due to its finite resolution (of camera system or human observer). To get better observations we have $\Delta l = \Delta O \pm \lambda \sin(\Delta \theta) \leq \Delta P$.

Hence the distance of aiming $\lambda$ can be computed as

$$\lambda \leq \frac{(\Delta P \pm \Delta \Omega)}{\sin(\Delta \theta)} \min$$

(9)

The distance computed by (9) is the optimum distance of the observation plane from the laser origin. Beyond this distance the magnification in error does not help in getting better joint angle data and within this distance the error magnification is not maximum.

The real robot has limited resolution. The resolutions of all joints for Staubli robot are shown in Table II. A large number (30000) of joint configurations spanning the workspace are determined. Two robots are created in simulation, one is moved to each of the joint configurations, and the other is moved to the same joint configurations but with offset equal to maximum joint resolution errors. The norm of the difference in position and the angle between laser lines are computed. The mean and standard deviation of these values for all joint configurations are computed. The mean and standard deviation of the norm of position error were $O_m=0.000236$mm and $O_s=0.0000577$mm respectively. The mean and standard deviation of the angle between laser lines were $\theta_m=0.00217$deg and $\theta_s=0.002583$ deg respectively.

If a camera system is used, the resolution of the camera system is 1 pixel which corresponds to the error of approximately 0.05mm in the observation plane. Hence we can safely use $\Delta P = 3 \times 0.05 = 0.15$mm which accounts for other errors in observations (computing center of laser point). If observations are taken by a human the resolution of observations can be around $\Delta P = 0.5$mm. The optimum distance of aiming computed by using (9) for camera system and human observation cases are $\lambda \approx 1800$mm and $\lambda \approx 6000$mm respectively. The average distance of the laser origin from base of the robot is around 1200mm for various joint configurations. Hence the optimum distance of the observation plane is $\beta \approx 3000$mm and $\beta \approx 7200$mm for camera system and human observation cases respectively.

VI. EXPERIMENTS

A. Calibration with Noisy Data in Simulation

Simulation of the calibration experiment was performed. A robot model was created in Simulink with a known set of parameters different from the industrial parameters (approximate DH parameters used by the robot manufacturer). The feedback system was used to accurately

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Actual values</th>
<th>Initial values</th>
<th>Minimum Error</th>
<th>STD (X10^-3)</th>
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<td>-0.171296</td>
<td>0.2718</td>
</tr>
<tr>
<td>$p_4$ (mm)</td>
<td>1.63</td>
<td>0</td>
<td>1.630099</td>
<td>3.1269</td>
</tr>
</tbody>
</table>
aim the laser tool at a fixed point from two different RTU locations (D=1000mm apart). The laser point is finely adjusted using the feedback loop as discussed in section IV.A until the errors in projected points were within ±0.0005mm and the joint configurations were recorded with full accuracy. A real robot joint has limited resolution and can only be commanded to move to a particular encoded value closest to the desired angle. Hence, to make the simulation more realistic noise is added to the joint values with magnitude of the maximum resolution. These joint configurations were used to calibrate the robot; the industrial parameter set was used as the initial solution. The solution was compared to the actual parameters used to generate the joint configuration data. The experiment was repeated with different fixed points and various sets of joint configurations. The deviations of the parameters from the actual parameters were computed.

Table III shows the results of the calibration with noisy data. Columns 2 and 3 show the true robot parameters used (matching closely to the real robot parameters obtained from next experiment) to obtain data and the initial parameters used in the minimization routine respectively. Columns 3 and 4 show the optimum solution and standard deviations from true parameters respectively. The standard deviation of the solution was small enough (10^-3) to justify that the procedure produces a usable result.

B. Calibration of Staubli Robot

The calibration experiment was performed on a real Staubli RX130 robot. We used the second method, i.e., the robot was translated (on an RTU we assume that the direction of the translation is unknown) and the laser was aimed at the same point. The experiment was repeated multiple times with different fixed points. The mean and standard deviations of the calibration parameters were computed.

Table IV shows the results of the calibration of the real robot. Column 2 shows the initial parameters used in the minimization routine i.e. the model parameters provided by the factory controller. Column 3 shows the optimum solution. Column 4 and 5 show the mean and standard deviation of the parameters and from multiple trials. The standard deviation of the solution was also small (10^-3) indicating the stability of the procedure.

C. Accuracy of Staubli Robot

To compare the accuracy of computed parameters with the industrial parameters, the laser was aimed at a fixed location using various robot joint configurations. The laser lines were computed for each position using industrial parameters and calibrated parameters. These laser lines usually don’t intersect at a common point hence an optimum 3D ‘closest point’ which is closest to all the lines was found in both cases. The projections of all the lines onto a plane passing through this ‘closest point’ were plotted. The larger the error in the parameters, the greater will be the scattering in the projected points.

The errors in the projection using industrial and calibrated parameters for a real robot are shown in Fig. 7. The maximum, mean and standard deviation of the radius of spread were 11.25mm, 5.64mm and 1.89mm respectively, using the original DH parameters built into the commercial controller and 4.22mm, 1.05mm and 0.587mm respectively, using calibrated parameters.

VII. LIMITATIONS

The present method of calibration does not take into account other sources of error such as temperature, load variations, and elasticity of the arms. Having a general model which includes other effects apart from the inaccurate geometric model can also be calibrated using the procedure herein. The robot should be able to connect to the laser tool or at least be able to hold the laser tool rigidly if there is no provision for tool interchange. Selection of a good laser whose light does not diverge much with the distance of projection is important.

VIII. CONCLUSIONS

An accurate calibration procedure is developed for industrial robots. Most of the previous methods that calibrate a robot use the pose of the end-effector measured by some instrument. The accuracy of measurements of the end-effectors position and orientation is limited by the measuring instrument and its resolution. Other closed-loop methods which use physical constraints such as linear, planar or other end-point constraints have limitations in obtaining accurate joint readings that satisfy the constraints. The proposed method uses a laser pointer tool on the robot’s end-effector to aim at a fixed location on a distant object. By projecting the laser pointer onto a distant object, the resolution of observations is improved, increasing accuracy of measurements of the joint angles required for accurate
calibration of the robot. The method is verified using both simulation and real experiments. It is also shown in simulation that the method can be automated by a feedback system.

ACKNOWLEDGMENT

This work was supported in part by the U.S. Department of Energy under Grant DE-FG52-04NA25590 issued to the University of New Mexico (UNM) Manufacturing Engineering Program. (Principal Investigators are J. Wood, R. Lumia, and G. Starr.) We would also like to thank Dave Vick who helped the authors with the experiments on the Staubli RX-130 robots and RTU.

REFERENCES