Precise Calibration of Robots with small link lengths using Kinematic Extensions

Visak Chadalavada[1] and Vikash Kumar[2]

***Abstract*— Complex anthropomorphic robotic hands with small link lengths and large number of degrees of freedom pose a unique challenge for calibration. The problem is interesting because the small magnitude of joint motion produced by small robots are difficult to capture by external sensors such as motion tracking systems. There is a need for a simple yet effective solution to this problem. In this paper, we show that a simple mechanical extension of the kinematic chain can be utilized to address this issue with good results. Using Standard motion tracking system and least squares optimization techniques, we identify joint sensor parameters. We also use finger tip loop closure distance, which is the distance between the thumb finger tip and the rest of the finger tips taken individually as an aid in estimating the true joint angles to calibrate the joint position sensors mounted on the hand. The results obtained are a significant improvement over the manual sensor calibration.**

I. INTRODUCTION

Replicating human like hand manipulation and grasping has been the goal of researchers in the field of robotics for quite sometime now. The development of robot technologies for different industrial applications has been continuously achieving new heights and now the expansions of robots to perform household activities is the next challenge in robotics. Advanced manipulation capabilities of robots are important to enable human-robot interaction or maybe even replace humans altogether.

Joint position information becomes crucial in a control strategy that can equip a robotic hand to perform advanced hand movements that humans are capable. Joint level sensor Calibration is an essential first step, but is a challenging and time-consuming process. The problem becomes even more tedious because anthropomorphic hands are complex robotic manipulators with many degrees of freedom. Borst et al. [1] and Cui et al. [2] describe teleoperation methods to control robotic hands, which require accurate mapping of joint angles. This emphasises the need for accurate calibration of joint position sensors.

The size, space and weight limitation on robotic hands prevent the use of advances sensory systems like optical encoders. In this paper, we propose a simple and effective technique for calibrating joint angle sensor for complex smaller robots with many degrees of freedom.

ADROIT (a modified Shadow Hand) is a tendon driven anthropomorphic hand with 24 dof, with more degrees of freedom than the human hand, it has capabilities that exceed human hand motion, Kumar et al [3]. The complex mechanical structure of the joints on the hand that gives the hand these amazing capabilities also preclude the use of bulky optical joint angle encoders. The hand relies on Potentiometers and Hall effect sensors for joint positions. These are not the best sensors available but to enable the hand to perform complex movements, accurate calibration of the the joint angle sensors is important. The kinematic structure of the shadow hand is shown in 1. The wrist is

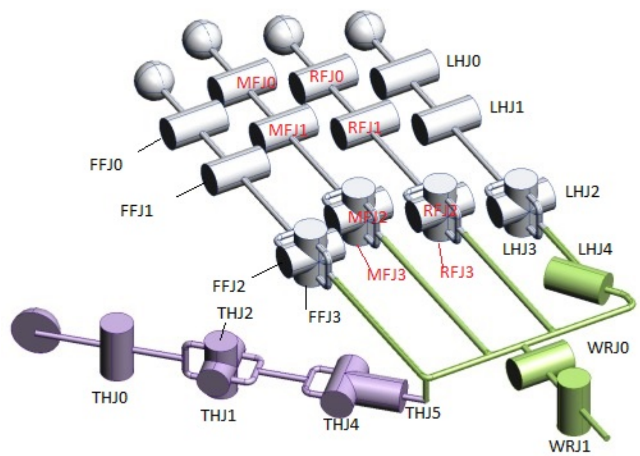


Fig. 1: Kinematic Structure of Shadow hand

made up of 2 joints, the index, middle and the ring fingers have 4 joints each, the thumb and the little fingers have 5 joints on them. There are mechanical stoppers that restrict the motion of the joints to a certain range.

Carrozza et al [4] used an optical method to calibrate the joint position sensors where a digital camera is used to capture different frames and the joint angle is calibrated using position of the joint measured using module Measure Tool of Adobe Photoshop 5.5. This requires the plane of motion to be perpendicular to the camera position, which might not be easy to execute with multiple degrees of freedom at one joint. The knuckle junction of ADROIT hand is made up of 2 joints, one that is provides up and down motion of the fingers and the other left and right motion. We have adopted a motion tracking system as an external sensor to calibrate ADROIT hand because it is the better way to capture the motion of manipulator with multiple degrees of freedom. Zollo et al [5] used an external infrared optical device for movement analysis, such a solution severely restricts the working environment of the robot.

Joint sensor level calibration using external tracking is an often overlooked topic for large robotic manipulators as they

1 Department of Mechanical Engineering, 2 Department of Computer Science & Engineering and Applied Mathematics, University of Washington, WA 98195, USA

E-mail: {vikash@cs.washington.edu,visakc@uw.edu

are equipped with better sensors and have a large range of motion that gives more information to accurately calibrate sensors. For smaller robotic manipulators, the issue of calibration poses a unique challenge. For example, ADROIT has a kinematic structure that is made up of small finger link lengths. This poses an issue with the calibration of the joints present higher in the kinematic chain, i.e. closer to the tip of the finger. For example,moving the joints at the base of the index finger say either $FFJ3$ or $FFJ4$ has a large effect on the position of the tip of the index finger, due to the large radius, where as the same cannot be said about the $FFJ0$, this means that the small movements of this joint is usually of the same order as the noise of the sensor measurement that will be used to calibrate the joint angle sensor.

Manual calibration of the joints is done using standard calibration jigs that requires the hand to be held in a specific pose that represent certain defined angles. The raw sensor values are calibrated with these angle measurements to get a calibration function that maps the the raw values to the joint angles. Owing to the complex mechanical structure of the hand, manual calibration can be hard to execute without inducing errors in the calibration. This method is particularly hard for the thumb which has a complex mechanical joint structure. The tedious process of manual calibration is not accurate enough.

In this paper, we propose a simple yet effective way to tackle the calibration issue arising from small link lengths and complex mechanical structure by using mechanical extensions at the end of finger tips that magnify the displacement which is captured by the motion tracking system. To reach our ultimate goal of estimating true joint angles from the motion tracking data we need accurate information about the position of the motion tracking markers on the hand while collecting the data and the transformation matrix for coordinate transformation, these are identified using numerical optimization, which makes this an reduced system identification problem. The forward kinematics required to solve the problem is calculated by Mujoco Physics engine [6]. Mujoco uses an accurate to CAD model of the hand to calculate the forward kinematics. We also utilize finger tip loop closure data, which is the data collected when the thumb and individual finger tips are brought in contact and moved around. This data was used in further calibration of joint sensors to increase the accuracy. The resulting calibration is validated using the finger tip loop closure test.

In the following section we go over some of the related work done previously. Section III our approach and the optimization phase are explained. Section IV gives the explanation of the experimental results followed by section V where we discuss the results of our approach and future work.

II. RELATED WORK

Karan et al [7] gives an overview of calibration accuracy and techniques used in calibrating robots. The calibration parameters for robotic manipulator system are sensor measurement, link lengths, link twists and in case of vision sensors sensor position as well, these need to be accurately identified for state estimation, control and planning purposes.

There are two approaches to robot calibration, one is based on measurement of predefined measurements and followed by mathematical optimization of parameters which best fit the measured positions. The second method is called the screw axis measurement method which identifies the real positions of the robot's axes and identifies the kinematic parameter using algebraic relations between the axes Hollerbach et al [8].

In recent years, Nubiola et al [9] reported absolute calibration of ABB IRB 1600 industrial robot by identifying 25 geometric errors using optimization and external laser tracker. Park et al [10] proposed a novel tecnique to estimate entire kinematic parameter error of a robotic manipulator, with Extended Kalman Filter to estimate the kinematic parameters. Santolaria et al [11] reported a method where the uncertainty of robotic kinematic calibration is estimated and therefore estimate robot positioning uncertainty. Wu et al [12] described a novel alternating optimization approach to simultaneously track joint angles and calibrate parameters (STAC). Although these papers report a lot more than just calibrating a robot, we intend to simplify the calibration method.

Wittmeier et al [13] showed how effective using a powerful physics engine can be in the process of steady state pose calibration. Eccerobot design study(EDS) an anthropomimetic robot was calibrated using physics based simulation engines to simulate complex dynamics and kinematics.

III. METHOD

A standard calibration procedure includes:

1) Modelling the system - Mujoco is used to calculate the forward kinematics.
2) Measurement of the true marker positions is done using Phase Space.
3) Identification of the calibration parameters is done using numerical optimization

Phase space motion tracking system gives us the $X_p \in R^3$ positions of the markers of the hand. The markers are infrared LEDs whose motion is captured by 8 cameras around the Adroit hand. The positions of the markers on the hand and the cameras are carefully chosen as the visibility of the markers while collecting data is important. To account for any joint that has an effect on the end position of the finger, 3 markers are placed on the fingers out of which one is on top of the extension and 1 on the palm, for the wrist joints. Each finger is individually calibrated.

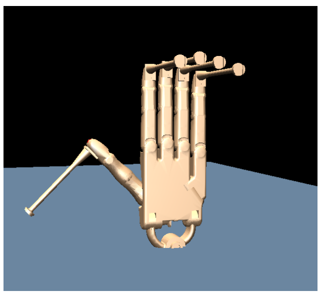
To calibrate a robotic manipulator, the forward kinematics plays an important role in providing information about the end effector position given a vector of joint angles

$$X = f(\theta, q)$$

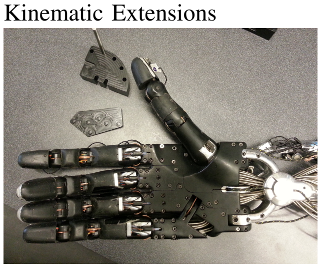
where $q \in R^n$, n is the number of joints and θ represents the kinematic parameters. The forward kinematics is done by the Mujoco physics engine, which uses an accurate CAD model of the shadow hand to do the forward kinematic calculation.

The position of any point pre-defined on the model can be obtained from Mujoco in the coordinate frame of the robot. We use the joint angle and site position data obtained form Mujoco to identify parameters in the optimization.

The marker position on real hardware is replaced by sites on the virtual hand model in MuJoCo. The positions of the markers are only done using hand measurements, which is why the optimization also includes estimating the correct site positions starting from an approximate model. The phase space markers give us position data in phase space coordinate frame, and the Mujoco model gives us the site locations from a different coordinate reference frame, this calls for the phase space data to be transformed into the Mujoco model's coordinate frame, this is also a part of the optimization routine.



(a) MuJoCo Hand Model with Kinematic Extensions



(b) The Adroit Hand

A. KINEMATIC EXTENSIONS

The kinematic extensions used on the the hand is shown in the 2a. The small lengths of the links gives rise to the following issue. The forward kinematics of the hand can be given as

$$X = forward(m, q)$$

But the joints that are higher in the kinematic chain and have small link lengths produces little effect at the tip of the finger. For example, consider the following optimization problem,

$$qhat = \underset{\mathbf{q}}{argmin}\,||PS(\hat{\mathbf{R}}) - forward(\hat{\mathbf{m}}, q) + \varepsilon||$$

The small change in the forward kinematics means that the magnitude is in the same order as the measurement noise which causes error in the optimizer results. Using the hand extensions $10cm$ each changes the forward kinematics in the following way,

$$X = \alpha \times forward(m, q)$$

This magnification in the end position changes the optimization such that the forward kinematics term is much larger than the noise in the measurement

$$\hat{\mathbf{q}} = \underset{\mathbf{q}}{argmin}\,||PS(\hat{\mathbf{R}}) - \alpha \times forward(\hat{\mathbf{m}}, q) + \varepsilon||$$

B. SITE OPTIMIZATION

The marker positions in the phase space coordinate frame X_ps is transformed into the robot's coordinate frame defined in mujoco X_m using the transformation

$$X_m =^M R_P \times X_ps +^M T_P$$

${}^M R_P$ is the rotation matrix and ${}^M T_P$ is the offset. The cost functions for optimization are defined as the following.

$$\{\hat{\mathbf{R}}, \hat{\mathbf{m}}\} = \underset{\{\mathbf{R},\mathbf{m}\}}{argmin}\,||PS(R) - forward(m, \hat{\mathbf{q}})||$$

optimizes for the the site locations on the hand.

$$\hat{\mathbf{q}} = \underset{\mathbf{q}}{argmin}\,||PS(\hat{\mathbf{R}}) - forward(\hat{\mathbf{m}}, q)||$$

optimizes for the joint angles and the parameters to be identified are

$$\psi = [\theta_x, \theta_y, \theta_z, t_x, t_y, t_z, X_s]$$

where θ_x, θ_y and θ_z are the euler angles that will give us the rotation matrix. t_x, t_y and t_z are the coordinate offsets and X_s are the site positions of the markers.

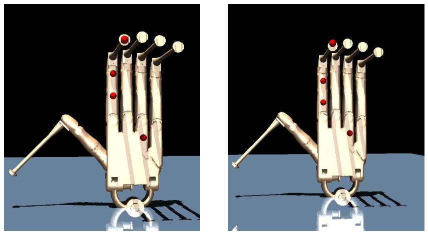
When the two cost functions converge, we obtain the transformation matrix and the optimized site locations. The optimization is seeded with initial guess for the transformation matrix and site positions. The initial guess for the transformation matrix can be obtained using procrustes analysis. The joint limits on the model also reduce the optimization space. The joint angles as well are initialized to the manual calibrated sensor readings from the sensor. The phase space data is transformed using the transformation matrix, this will represent the marker positions in Mujoco's coordinate frame more accurately. The transformed data is used to predict the joint angle positions of the finger and wrist joints that minimize the error between the site position on mujoco hand model and the transformed Phase space data.

C. FINGER TIP LOOP CLOSURE OPTIMIZATION

The thumb has 5 degrees of freedom and the hub joint that connects the thumb to the palm has a complicated joint structure and the motion of the joint is such that the tracking of the Phase space motion markers is not possible for the entire range of motion of these joints. To address this issue, the base joints of the thumb are calibrated again using the the finger tip loop closure idea, where the distance between the finger tips between index and thumb is minimised and the joint angles of just the base joint of the thumb are estimated as optimization parameter $\gamma = [\gamma_1 \gamma_2]$. The cost function is defined as

$$\hat{\mathbf{q}} = \underset{\mathbf{q}}{argmin}\,||forward(m, q_{index}) - forward(m, q_{thumb})||$$

Here $\hat{\mathbf{q}} \in R^2$ as only two joints are estimated as parameters.



(a) Before Identifications (b) Identified site locations

D. JOINT ANGLE OPTIMIZATION

The joint angle obtained is taken as the true joint positions and the raw sensor values is calibrated by minimizing the following cost function. The manual calibration is used as initial values for the optimization.

$$\hat{\mathbf{c}} = \underset{\mathbf{c}}{argmin}\,||\hat{\mathbf{q}} - calib(q, c)||$$

This approach is applied to all the joints on the hand and the calibration file that maps the raw data to the joint angles is obtained.

E. CALIBRATION MODEL

Potentiometers can be calibrated using an affine model, where as the model for the hall effect sensor needs to be non linear and carefully chosen so that a single function can fit the data from all the joints that have the hall effect sensor. The potentiometers are calibrated using

$$\hat{q} = \frac{x - \mu}{\sigma}$$

The model for the non-linear joints is chosen as

$$\hat{x} = \frac{x - \mu}{\sigma}$$

and over this a non-linear function is used

$$\hat{q} = \frac{p1\hat{x}^3 + p2\hat{x}^2 + p3\hat{x} + p4}{\hat{x}^2 + q1\hat{x} + q2}$$

The optimization estimates $\{\mu, \sigma, p1, p2, p3, p4, q1, q2\}$.

IV. EXPERIMENTAL RESULTS

The optimization is able to correctly identify the site positions and the transformation matrix. The site positions estimated agree well with the ground truth of the marker location on the real hardware as shown in 3a and 3b.

The joint estimates at FFJ2 is shown in 4 The optimized calibration is close to the manual calibration in all the joints except the thumb, which is particularly hard to calibrate manually because of the complex hardware that makes up the thumb joints. The thumb also plays a crucial role in recreating human like motion, so right joint position calibration of the thumb is important. The potentiometers are calibrated using a linear function. Where as the magnetic sensors are calibrated using a non linear function, which are the knuckle joints and the wrist joint of the hand.

5 shows the difference in manual calibration and and the joint angle estimates from the optimization.

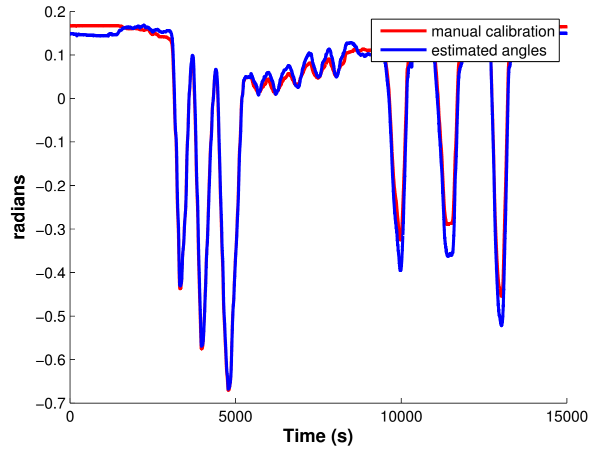


Fig. 4: Estimated joint angle by optimization

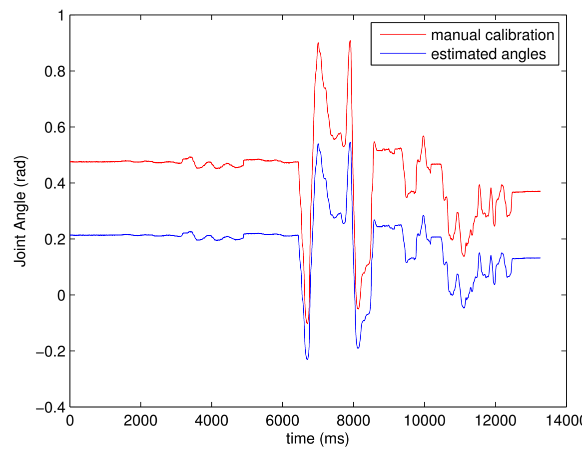


Fig. 5: Thumb finger, manual and optimized calibration

The improvement of the calibration of thumb is validated in the finger tip test where the optimized calibration produces much less error than the manual calibration.

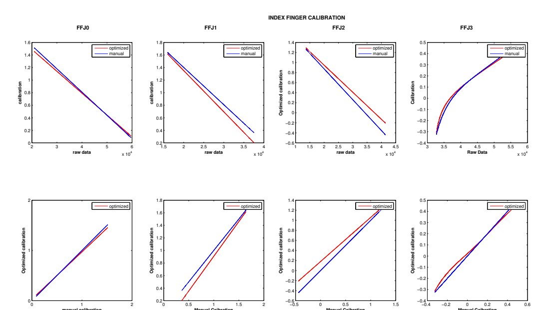


Fig. 6: Index finger, manual and optimized calibration

A. FINGER TIP LOOP TEST

The finger tip loop test is the best test to judge the goodness of calibration of the joint sensors, for example,

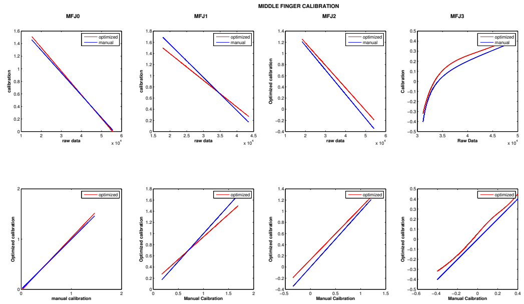


Fig. 7: Middle finger, manual and optimized calibration

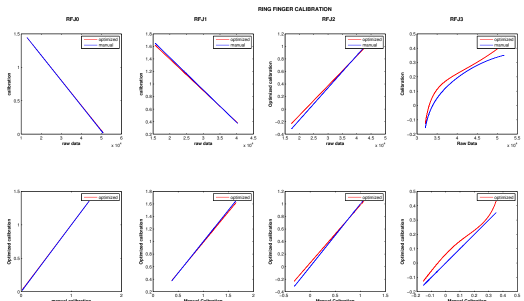


Fig. 8: Ring finger, manual and optimized calibration

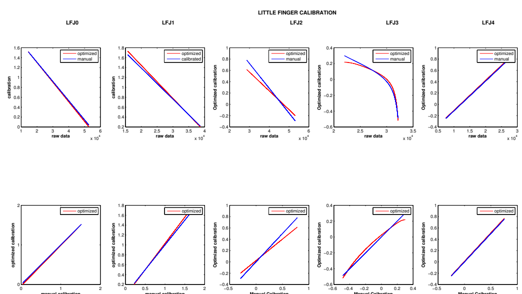


Fig. 9: Little finger, manual and optimized calibration

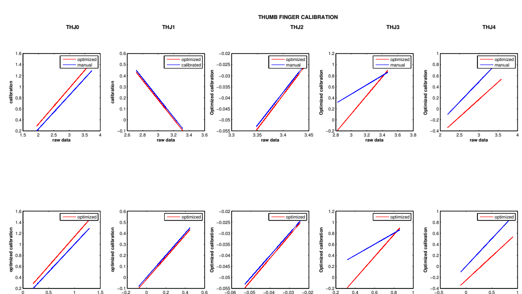


Fig. 10: Thumb finger, manual and optimized calibration

when the loop is closed by holding the tip of the index finger and the thumb finger close together and moved around , only the right calibration of the joint sensors can reproduce the same movement in simulation. The figures $11-14$ show the reduced error in the finger tip test compared to the test done with manual calibration of the sensors. This validates the optimization approach to calibrate the joint angle sensors. The finger tip test is done placing sites at the tips of the Mujoco model, then calculating the distance between them at each time step as the joints move around. The slight increase in distance error while using the optimized calibration can be reasoned by the fact that the loop test involves a rolling contact at the tips rather than contact at a single point, whereas the error distances were calculated using points at the tips of the fingers as reference to calculate the distance function.

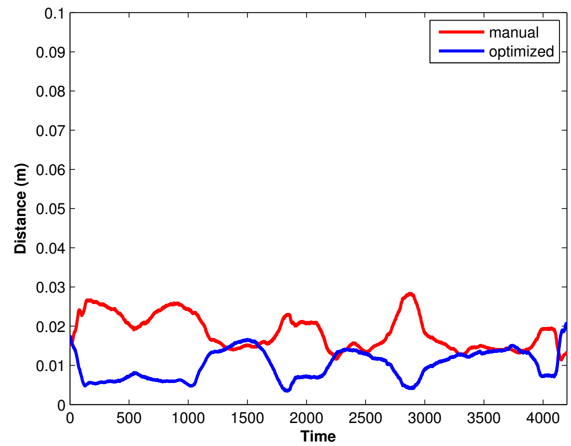


Fig. 11: Index finger loop test error

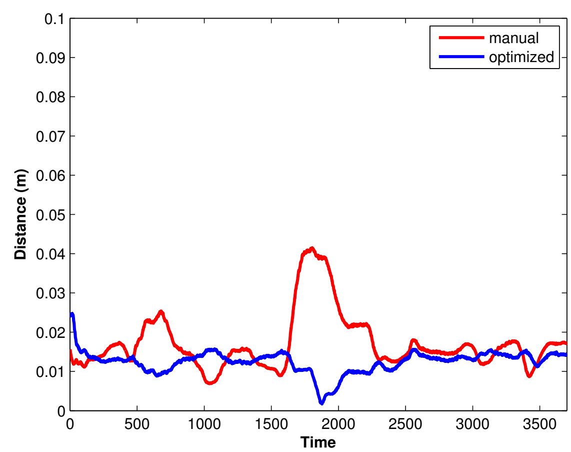


Fig. 12: Middle finger loop test error

15b and 15a show the difference and improvement in the calibration.

V. Conclusions and Future Work

In this paper, we have presented a simple and effective way to calibrate robots that are complex with small link lengths and large number of degrees of freedom. In addition to standard calibration technique of measuring the true joint values

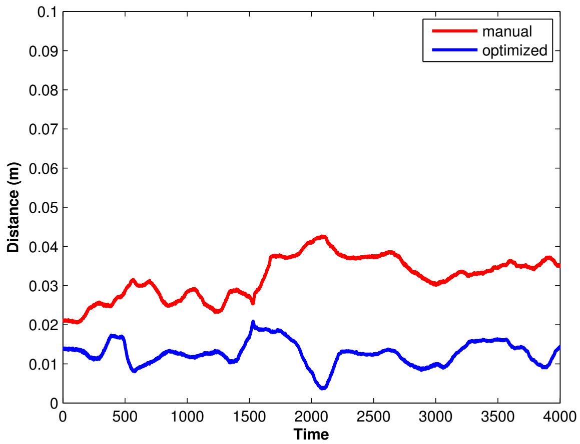


Fig. 13: Ring finger loop test error

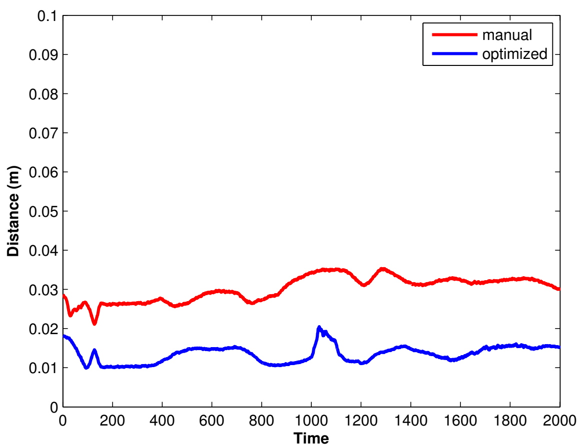
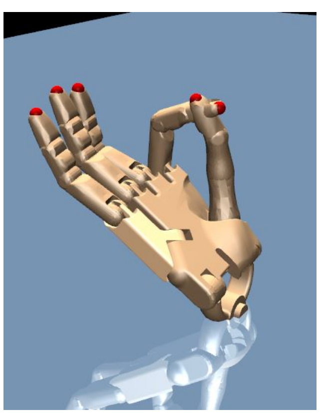
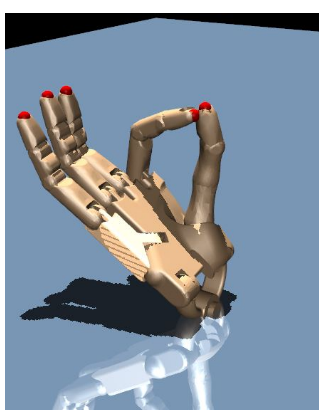


Fig. 14: Little finger loop test error



(a) Manual calibration



(b) Optimized calibration

with an external sensor and using mathematical optimization to identify the parameters that best fit the measurement, we introduce using finger tip loop closure as an effective method to calibrate and to validate the calibration.

In doing the finger tip loop closure test, single point sites were considered to calculate the distance between the tips of the fingers, whereas in reality there is a rolling contact between the tip during the finger tip closure test. This will be addressed to improve the calibration further. The idea of finger tip loop calibration test can be leveraged and used to calibrate all the joints without the need for external motion tracking would greatly reduce cost burden on the equipment. This idea of finger tip loop closure test will be pursued in future work.

References

[1] C. Borst, M. Fischer, S. Haidacher, H. Liu, and G. Hirzinger, “DLR hand II: experiments and experience with an anthropomorphic hand,” *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)*, vol. 1, pp. 14–19, 2003.

[2] L. Cui, U. Cupcic, and J. S. Dai, “An Optimization Approach to Teleoperation of the Thumb of a Humanoid Robot Hand: Kinematic Mapping and Calibration,” *Journal of Mechanical Design*, vol. 136, no. 9, p. 091005, 2014. [Online]. Available: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?articleid=1877636

[3] V. Kumar, Z. Xu, and E. Todorov, “Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hands,” *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 1512–1519, 2013.

[4] M. C. Carrozza, B. Massa, S. Micera, M. Zecca, and P. Dario, “A Wearable Artificial Hand for Prosthetics and Humanoid Robotics Applications,” *IEEE RAS International Conference on Humanoid Robots*, p. 7, 2001.

[5] L. Zollo, S. Roccella, E. Guglielmelli, M. C. Carrozza, and P. Dario, “Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications,” *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 4, pp. 418–429, 2007.

[6] E. Todorov, T. Erez, and Y. Tassa, “MuJoCo: A physics engine for model-based control,” *IEEE International Conference on Intelligent Robots and Systems*, pp. 5026–5033, 2012.

[7] B. Karan and M. Vukobratović, “Calibration and accuracy of manipulation robot modelsAn overview,” *Mechanism and Machine Theory*, vol. 29, no. 3, pp. 479–500, 1994.

[8] J. M. Hollerbach and C. W. Wampler, “The calibration index and taxonomy for robot kinematic calibration methods,” *The International Journal of Robotics Research*, vol. 15, no. 6, pp. 573–591, 1996. [Online]. Available: http://ijr.sagepub.com/content/15/6/573.abstract

[9] A. Nubiola and I. a. Bonev, “Absolute calibration of an ABB IRB 1600 robot using a laser tracker,” *Robotics and Computer-Integrated Manufacturing*, vol. 29, no. 1, pp. 236–245, 2013. [Online]. Available: http://dx.doi.org/10.1016/j.rcim.2012.06.004

[10] I. W. Park, B. J. Lee, S. H. Cho, Y. D. Hong, and J. H. Kim, “Laser-based kinematic calibration of robot manipulator using differential kinematics,” *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 6, pp. 1059–1067, 2012.

[11] J. Santolaria and M. Ginés, “Uncertainty estimation in robot kinematic calibration,” *Robotics and Computer-Integrated Manufacturing*, vol. 29, no. 2, pp. 370–384, 2013.

[12] T. Wu, Y. Tassa, V. Kumar, J. Movellan, and E. Todorov, “STAC: Simultaneous Tracking and Calibration,” *Homes.Cs.Washington.Edu*, 2013. [Online]. Available: http://homes.cs.washington.edu/~vikash/Projects/STAC/STAC.pdf

[13] S. Wittmeier, A. Gaschler, M. Jantsch, K. Dalamagkidis, and A. Knoll, “Calibration of a physics-based model of an anthropomimetic robot using Evolution Strategies,” *IEEE International Conference on Intelligent Robots and Systems*, pp. 445–450, 2012.