INVESTIGATION INTO A MULTILATERATION LASER TRACKING SYSTEM FOR THE NATIONAL METROLOGY INSTITUTE OF SOUTH AFRICA

G.P. Greeff* and O.A. Kruger **

* National Metrology Institute of South Africa, Dimensional Laboratory, Private Bag X34, Lynnwood Ridge, Pretoria 0040, South Africa. E-mail: pgreeff@nmisa.org
** National Metrology Institute of South Africa, Dimensional Laboratory, Private Bag X34, Lynnwood Ridge, Pretoria 0040, South Africa. E-mail: oakruger@nmisa.org

Abstract: A baseline study for the implementation of multilateration with a laser tracker for the Dimensional Laboratory of the NMISA (National Metrology Institute of South Africa) was completed. Software which requires one laser tracker to perform sequential multilateration was developed for the lab. Simulation studies are also done with this program for verification and configuration motivation purposes. Other aspects of the study involved developing a prototype laser tracker station and performing kinematic simulation analysis on gimbal type trackers. With practical experience gained, recommendations are made for future multilateration development in the Dimensional Laboratory.

Keywords: Multilateration Laser Tracker, Three Dimensional Coordinate Measurement, Dimensional Metrology

1. INTRODUCTION

The NMISA (National Metrology Institute of South Africa) is responsible for development, dissemination and maintenance of the national standards. The Dimensional Laboratory of the NMISA is responsible for maintaining the national standard of length, an iodine stabilised He-Ne laser. Part of the responsibilities of this group is to provide traceability from this national standard for three dimensional measurement systems.

Fast and accurate three dimensional measurements are critically to the manufacturing industry. Various instruments are used to measure individual parts as well as the alignment during the assembly processes of large scale projects. Measurements are required from projects such as ship building and aeroplane construction, to smaller products such as rotor blades, satellite dish antennas, turbines and the motor industry. Basically, any manufactured product needs to be measured dimensionally, at some stage, for assembly or quality assurance purposes. Measurement instruments used include photogrammetry systems, bridge type CMMs (Coordinate Measuring Machine), portable measurement arms, total stations, indoor GPS systems and laser trackers [1].

Currently commercial laser trackers, utilizing interferometric laser distance measurements and angular encoders, remain one of the most versatile and accurate three dimensional measurement systems. This accuracy can be further improved by using a technique called multilateration, where only the distance component of multiple trackers is used to calculate the target point coordinates. A multilateration system is therefore directly traceable to the metre, reducing uncertainties caused by intermediate calibration steps, and eliminating the less accurate angle measurements [2].

Note that a technique where only one tracker is used to perform multilateration is called sequential multilateration. This technique is more feasible to implement, given the cost of laser trackers [3]. The repeatability of the target points will however affect the obtainable absolute accuracy.

The level of the required accuracy of dimensional metrology in manufacturing industries is increasing and this is the main motivation for the project; i.e. the need for more accurate coordinate metrology for the NMISA. This article will briefly explain how a tracker works, report on a prototype built and describe the concept of multilateration, as well as report on results of the project. The article starts with commercial laser trackers, as the building block for a multilateration system, which either uses more than one tracker, multilateration, or one tracker positioned at different locations, sequential multilateration. The main focus however of the project is to investigate the concept of multilateration for the purpose of practical laboratory implementation.

2. THE LASER TRACKER WORKING PRINCIPLE

The concept of the current commercial laser tracker, patented by [4], consist of the following main components: a laser source, a beam steering mechanism with angle encoders, an interferometer block, an optical sensor called a Position Sensitive Diode (PSD), beam splitting optics, a retroreflector, a control unit and software. These components are used to both track the target and measure the coordinates of the target (see Figure 1).

The source beam is split with a beamsplitter into a measurement and reference beam. The measurement beam travels from this beamsplitter to the target (the retroreflector) and back. After returning from the target it will interfere with the reference beam and this interference will be used to determine the relative change in distance to the target.

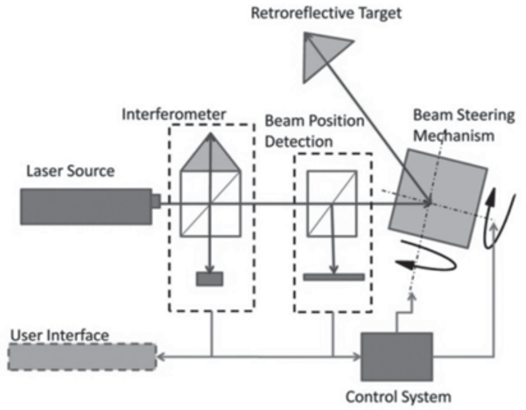

Figure 1: Schematic of Laser Tracker Components (Based on [4])

The measurement beam is steered towards the target with a mirror mounted on the beam steering mechanism. If the returning measurement beam does not return sufficiently onto the reference beam the interferometer will loose its reference and not be able to determine the change in distance to the target. The target therefore needs to be tracked, by minimizing the measured displacement between the outgoing and returning measurement beam (see Figure 2).

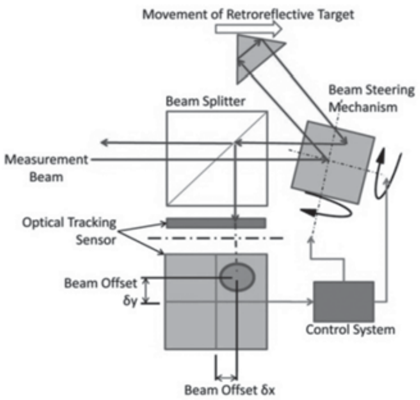

Figure 2: Schematic of Tracking Operation

This displacement is detected with the PSD. The optical sensor has four electrodes, each of them producing an amount of photo-current relative to the distance of the electrode to the centre of the beam spot. These photocurrents are amplified and converted to four voltages, which are used to determine the position of the centre of the beam on the sensor's active area [5]. The controller uses the detected offsets to minimize the tracking error by rotating the beam steering mirror to re-centre the beam on the PSD.

Note that an ADM (Absolute Distance Measurement) system does not need to track a target, while a distance interferometer system does. However current commercial interferometer systems are more accurate than current commercial ADM systems. The interferometer measurement is only a relative distance, not an absolute one. This affects a tracker in two ways: (1) an initial offset distance is needed and (2) that the target must be tracked at all times. There are commercial systems which combine both ADM and interferometer systems, mainly to enhance the speed and ease of measurements. Work however is being done to improve ADM accuracy to achieve sub-fringe resolution [6]. If ADM technology replaces the relative interferometric system, the target would not need to be continuously tracked any longer.

The three dimensional coordinates of the target is determined with two angles and one radius: the two encoder readings and the interferometric length measurement plus an initial offset distance.

This offset distance is relative to a home position. It is ideally equal to the difference between the distance from the measurement beam incident point on the beam steering mirror to the target point and from the same incidence point to the home position.

3. LASER TRACKER PROTOTYPE

A prototype laser tracker was designed and built to evaluate the feasibility of building a precision laser tracker for multilateration purposes. As well as to better understand the engineering challenges, scope and design parameters involved in such a project. The focus was specifically on the tracking sub-system (Figure 2), since the distance interferometric sub-system is well understood and easily implemented as a modular unit.

The prototype design involved (1) designing and building a beam steering mechanism, (2) sensor signal conditioning and (3) control of the system. For this project a single mirror gimbal was selected (Figure 3) for the beam steering mechanism, as it was the least complicated mechanism.

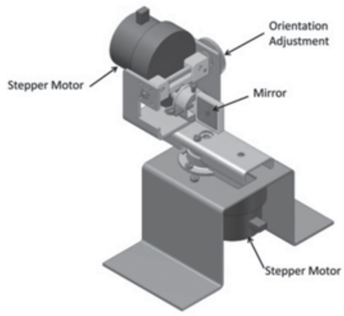

Figure 3: Drawing of the Prototype Tracker

An amplifier circuit, consisting of a current to voltage converter and amplification unit, was designed for the signal conditioning and for control of the system a microcontroller (dsPIC30f4011 from Microchip) was used. The microcontroller receives commands from a GUI (Graphical User Interface) on a PC via a RS232 connection. It also converts the sensor signals from the amplifier with an ADC (Analogue to Digital Converter), from which it determines the required commands to actuate the beam steering mechanism.

Four concepts are found in literature for the beam steering mechanism: gimbal [4], hemi-spherical [7], two mirrors [5] and spherical [8]. The gimbal is a single mirror (see Figure 3) beam steering concept. The hemi-spherical concept places the mirror on the flat of a hemi-sphere, and the two mirror concept uses a separate mirror for each axis of rotation. The spherical concept rotates the interferometer block around a reflective sphere.

A gimbal type beam steering mechanism was selected and is actuated with two geared stepper motors, driven with PWM (Pulse Width Modulated) signals via an H-bridge. The steppers are micro-stepped, to make the step resolution finer, by providing it with a micro-stepping sequence. A single beam laser tracking system consists of different components and interfaces. If this is joined with optical design and laser requirements, it becomes clear that such a system is a unique optical, mechanical and electronic engineering design challenge.

3.1 Laser Tracker Prototype Tests

Tests were performed with the prototype, to investigate the tracker's tracking ability. It was found that the system can track a target moving in a volume of 200x200x200 mm^3, at a distance of 300 mm from the tracker. It was decided that this is sufficient evidence for the working of the prototype station.

Table 1: New Specifications (Based on [9])

Parameter	Prototype	Ideal Specification
Angular Resolution	0,06 - 0,004 °/step* (1047 - 70 µrad)	0,0006 °/step (10 µrad)
Angular Speed	Not measured	10 m/s
Angular Acceleration	Not measured	19 m/s^2

*Minimum theoretically, with 16 bit microstep resolution

Testing of the prototype showed that fast direction change, very small step size and accurate positioning are the critical parameters for the beam steering mechanism. Table 1 quantifies the ideal specifications, based on existing system specification found in literature. A backlash free actuator will also increase the direction change speed.

3.2 Kinematic Modelling of a Gimbal Type Tracker

The kinematic model of [10], describes a two axis gimbal type laser tracker, ten parameters were used and simulated. This was done to gather a better understanding of a single laser tracker and its error sources. The model only focuses on the measurement error due to the beam steering system and does not account for errors in the retroreflector or the PSD.

The simulations were used to investigate how the measurement is influenced by various factors. Monte Carlo analyses were used to do these investigations. This is done with a set of Target Point (TP) coordinates. The target points formed a regularly spaced array in three-dimensional space and the simulation replicated the measurement of this array with a tracker. Uncertainty or errors were added to the tracker parameters, to investigate the spatial error effect of each parameter individually and combined.

The most significant conclusion of these simulations confirmed another study's results [11] and was that any lack of orthogonality between the rotation axes is a major cause of a shifting centre of rotation. The incidence point and the centre of rotation are consequently not coincident, which creates an error in the interferometric dead path, since the interferometer assumes the distance from the interferometer to the first point remains constant [9].

4. MULTILATERATION

4.1 Multilateration Concept

Multilateration is similar to trilateration (the determination of a target point, if three station points are given, along with the distance from each station point to the target point) with the main difference that the station point locations are not exactly known. However, if there are four station points a redundant equation, in terms of trilateration, will be obtained per target point. If sufficiently accurate initial target and station point coordinates, along with accurate lengths, are given, then the exact point coordinates can be solved (approximated) by a non-linear least square optimiser. The offset interferometric distance is also included as a variable in the optimiser. The optimiser then seeks the best fit for each tracker's offset distance and all the target point coordinates.

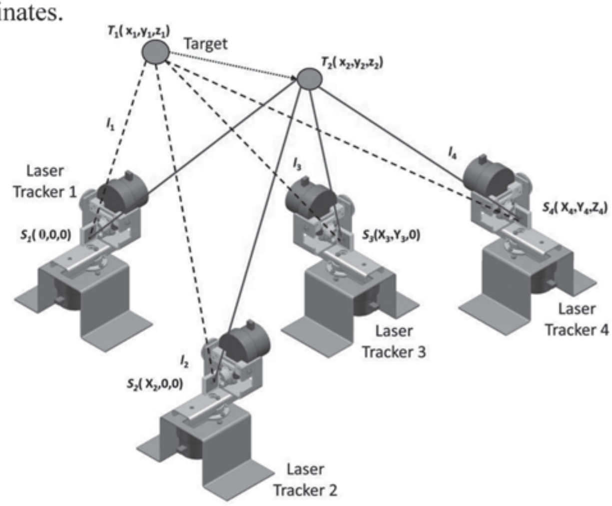

Figure 4: Schematic of a Multilateration Laser Tracking System, with Four Trackers. (Note the assumed initial position of the trackers, to reduce the number of variables)

A MLTS (Multilateration Laser Tracking System) therefore consists of a number of laser trackers (see Figure 4), coupled to software which performs post processing. Some MLTS use purpose built trackers, which do not have angle encoders [8], whilst others use the encoders to improve the measurement, by compensating for the tracking mirror centre rotation errors [12].

A MLTS satisfies the Abbé principle (i.e. the axis of measurement should be inline with axis of displacement to be measured), has direct traceability to the length standard, is self-calibrated with respect to its own position and is therefore superior to the conventional bridge-type CMMs [2,10]. For example, to measure any point the bridge type CMM must measure distances along three axes (X, Y and Z) sequentially, whilst a MLTS achieves this directly, without an Abbé error. The positional self-calibration of a MLTS also creates a virtual metrology frame, making it more portable [8] than a conventional CMM. The measurement range can be extended by only moving one tracker base station at a time. This allows, for example, the measurement of an object from all sides. [13] add that such a system (after self-calibration) can determine the position of the target or the initial distance for a laser tracker, in the event of one of the trackers losing the target. This overcomes the main limitation of an interferometric laser tracker: that the target must be tracked at all times. Self-calibration also negates the requirement for tedious measurement preparations [2].

A disadvantage of such a multilateration system is that the measurement volume is limited, compared to a single beam system [5]. High speed tracking is also vital, which necessitates an advanced control system, as shown by [14]. Furthermore, a laser tracker is an expensive system.

The MLTS software determines the offset distances and coordinates of the targets and tracking stations by using a non-linear least squares optimiser. The least squares algorithm tries to fit all the system variables to all the length measurements. The measurements are defined as the distances from the tracker mirror centre of rotation to the targets. The system variables are defined as the tracker coordinates, the offset (reference) length of each tracker and the target variables.

For n target points and four trackers, there are $3n$ target variables and $4n$ known measurements values. This implies that at least ten target points are required to solve the whole system. The coordinate system can be fixed, without loss of generality, by three assumptions regarding the positions of the tracking stations: the first station is at the origin *(0,0,0)*, the second tracker is only displaced in the X direction *(x,0,0)* and the third tracker is in the XY plane *(x,y,0)* [2].

The unknown variables (for n target points and m tracker stations) can be solved, given the required initial (estimated) values for system variables by minimizing the total system cost, or cost function, defined as:

$$E = \sum_{j=0}^{m} \sum_{i=0}^{n} {e_{ij}}^2 \qquad (1)$$

The residual e_{ij} for the j^{th} measurement station and i^{th} target point is [2]:

$$e_{ij} = \sqrt{\left(x_i - X_j\right)^2 + \left(y_i - Y_j\right)^2 + \left(z_i - Z_j\right)^2} - \left(l_{ij} - L_j\right) \qquad (2)$$

with the target coordinates $(x, y, z)_i$, the measurement station coordinates $(X, Y, Z)_j$ and the distance measured (l_{ij}). Note that all the length measurements (l_{ij}) are relative to an initial length (L_j) for each tracker. The length measurements are therefore given by ($L_i + l_{ij}$), where l_{ij} is the actual interferometric length measurement.

For the initial (estimated) values the measurements of the first tracker are used for the target point coordinates. The position of each tracker station relative to the first station is measured and this is used to provide all the initial stations' coordinates.

4.2 *Sequential Multilateration Test*

A Python program was developed at NMISA, based on the concept described above. Given a set of measured lengths and estimated initial positions for the tracker stations and target points, it searches for a possible fit, which minimizes the cost function (1).

Tests were done at NMISA using a commercial laser tracker and a CMM, in the Dimensional Laboratory. A magnetic retroreflective target holder was mounted on the CMM, which was programmed to move to five points (four corners and a middle point) in four vertical planes as shown in Figure 5. The tracker was positioned at 6 different points, around the CMM. The target was tracked and when the CMM came to a halt at a point, a measurement was taken. All 20 target points were measured from each of the 6 locations.

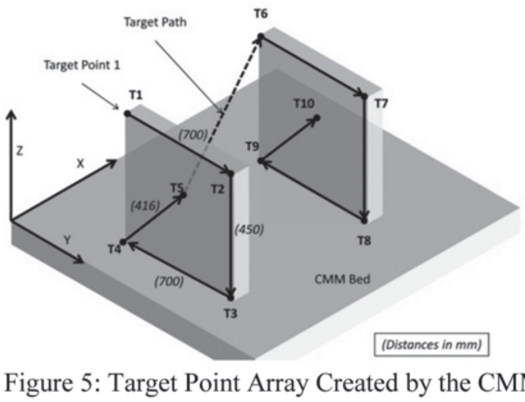

Figure 5: Target Point Array Created by the CMM

A local minimum for the cost function was found by the program for the system variables and measurements. The initial cost of the system was around 3250 mm. This was reduced to 10,054 µm.

The optimiser uses either its own numerical approximation for the Jacobian of cost function, or a user defined analytical matrix. An analytical Jacobian was used and it reduced the number of function call dramatically (300 to 7 iterations). The final cost though stayed the same (at 10,054 µm).

The commercial laser tracker software however does not output the raw interferometric length, only the post-processed absolute coordinates relative to the tracker's home position. The initial length variables were therefore suppressed in the algorithm. Since the same tracker is used for all the measurements, it is assumed to have a negligible effect in the comparison between the individual tracker and the algorithm result.

Table 2: Estimated Maximum Uncertainty

Uncertainty Contributor	Specification (µm, L in m)	Contribution (µm)
CMM	$(2{,}4 + 3L_c)^*$	5,4 (Max L_c: 1 m)
SMR and Tracker Repeatability	10,7	10,7
Tracker: Radial Transverse	 $(1 + 1L_r)$* $(3 + 1L_t)$*	7,55** (Max L_r: 4 m) (Max L_t: 1 m)

* From manufacturer specification

** $\sqrt{(1+4)^2 + 2(3+1)^2} = 7{,}55$

The accuracy of the system variables, which gives the local minimum, was further investigated using three dimensional distances. Such a distance between TP (Target Point) *i* and *j* is calculated with Pythagoras as:

$$d = \left|TP_i - TP_j\right| \tag{3}$$

All the possible three dimensional distances can be calculated for an array of TP. The resulting array from the optimizer (or fit) can then be compared with the individual tracker measurements and the expected CMM movement. The CMM movement however will not be ideal, but should be within an uncertainty. The fit and measurements can still be compared with the ideal CMM movement and should fall within this uncertainty. From Table 2 the maximum expected error for a point can be calculated by taking the sum of all the contributions, which is 23,7 µm, multiplying this with two, gives an estimate of maximum expected error in the distance between any two points, which is 47,3 µm.

Figure 6 shows the average deviation for four significant distances: the 200 mm X axis, 700 mm Y axis, 450 mm Z axis and 416,083 mm YZ distance. The measurements in the graph fall within the expected range, whilst the fit result falls outside the range for the Z and Y axes distances. This result is useful, since it gives a method to evaluate the accuracy of the fit, apart from the cost function. The cost function therefore is not a sufficient indication for the accuracy of the resulting fit.

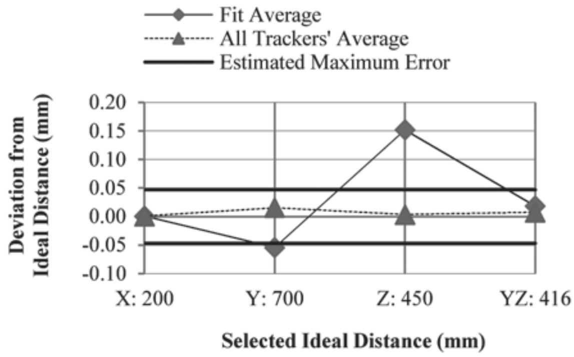

Figure 6: Average Deviation from Ideal CMM Distances (For the fit and the average of all 6 tracker positions).

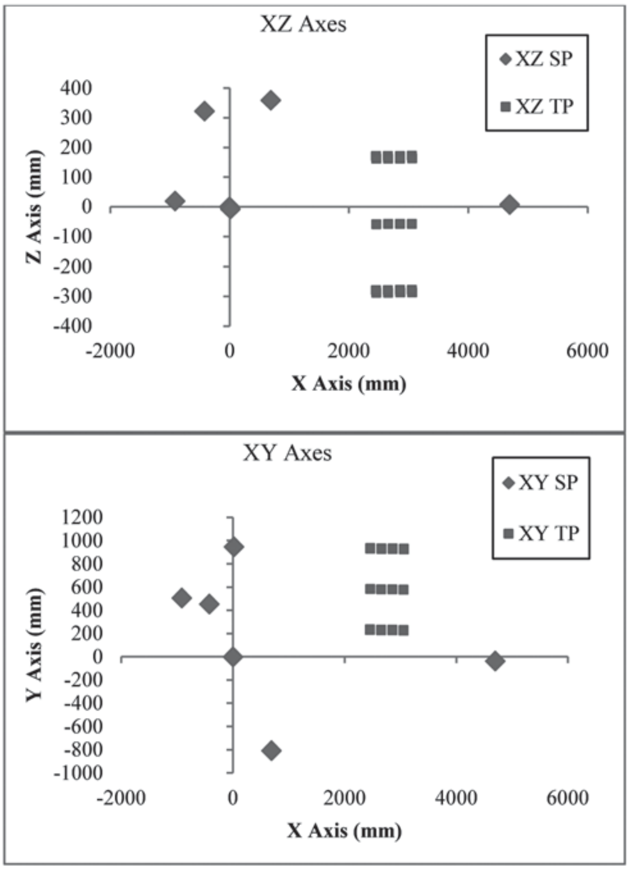

Figure 7: Configuration for Test (SP: (Tracker) Station Point)

4.3 *Improving the Sequential Multilateration Test Configuration*

Unfortunately the tracker used for the test stopped functioning and further tests could not be performed. Simulations however were used to test and improve the algorithm. Figure 6 showed a large deviation in some of the distances. The cause for these discrepancies is thought to be the configuration of the tracker stations around the TP array (see Figure 7).

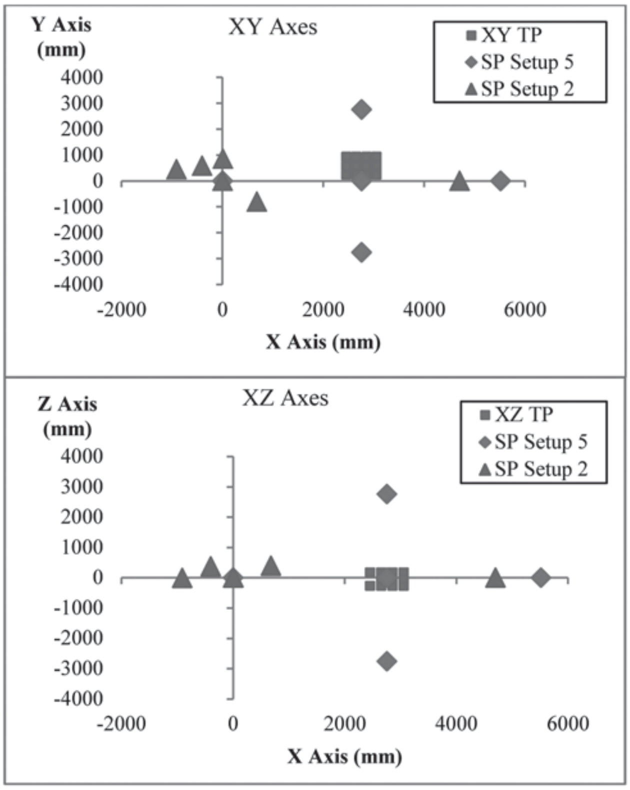

Figure 8: Different Configurations for the Simulations

During the experiment, only two of the six positions were elevated in Z direction, with only about 350 mm. In comparison the positions spanned the X axis with 5 m and the Y axis with 1,2 m. Basically, it gives more information for the solver in the X and Y directions, leaving more uncertainty in Z axis. This consideration is further motivated by [13,15,16]. Based on this, simulations were made which replicate the experimental setup and other configurations, for simulation verification and configuration improvement purposes. Figure 8 shows two of the five different configuration setups used. Note that setup 2 is similar to the test configuration.

Figure 9 depicts the average deviation for the different configurations for the simulations. This was obtained through taking the absolute of the average of 5000 Monte Carlo iterations for each setup. This result gives evidence that the simulation obtains the same type of error for a configuration similar to test setup. It also confirms that the configuration affects the obtainable accuracy. Setup 5 is clearly the most ideal configuration, of the five used. This setup however is not practically feasible, if a corner cube type retroreflector is used, due to the acceptance angle limitation of this type of target. A cat's eye retroflection however can reduce this constraint [17].

The number, location and configuration of the TP and the number of tracker locations used for the positional self-calibration will also affect the accuracy of the program. This can be simulated with the program. See [13,15,16] for guidelines on calibration configuration selection.

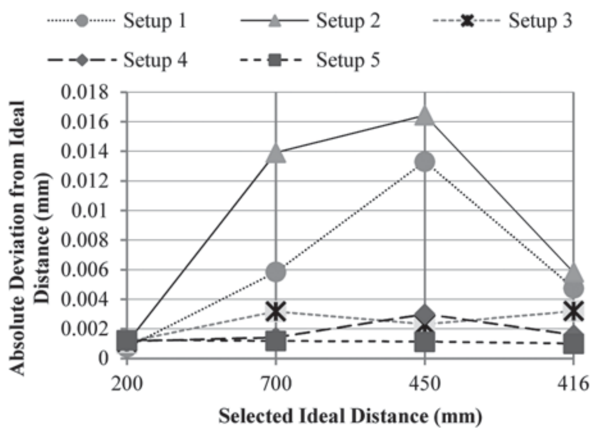

Figure 9: Average Deviation for the Different Configurations

5. MULTILATERATION SIMULATION

Simulations were done to investigate if the program can improve on the result obtained by a laser tracker or the average of multiple trackers. It was assumed that a sufficient number of trackers were available for these simulations.

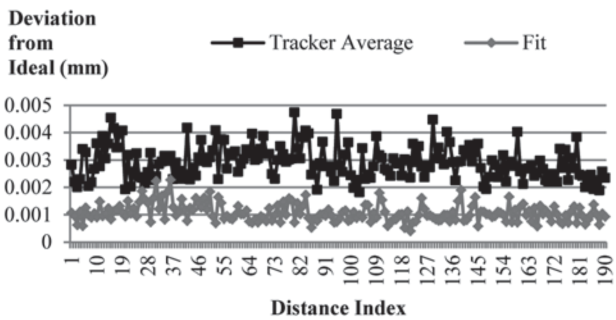

Figure 10: Average Deviation from Ideal Distance for Fit and Simulated Tracker Measurements

Figure 10 is a graph comparing the average of ten iterations of the simulation program, with six tracker stations arranged as setup 5 measuring simultaneously. All possible distances in a 20 point array were calculated and compared.

A 37% improvement on average is found and this illustrates the benefit of multilateration. The three dimensional distance comparison does give a better indication to the accuracy of the system variables than the final cost. The accuracy of the fit system variables compared against the tracker and tracker average measured values however still needs to be investigated.

6. CONCLUSION

A laser tracker is a highly accurate measuring instrument, with many applications in the coordinate measurement field. The concept of multilateration is able to even further improve this accuracy. The multilateration and simulation program which was developed and can be used by the Dimensional Lab to further study multilateration in the future. The prototype also gave insight into tracker station requirements.

Multilateration however is complex to implement with the optimisers' dependence on initial values and system configuration. Other accuracy constraints are the beam steering mechanism's dead path error contribution and, if sequential multilateration is used, the repeatability of the target points.

The investigation also found that the final cost at the local minimum is not a sufficient indication of whether the solver found a good fit for the measured data. Another comparison is needed, for example three dimensional distances or absolute point coordinates.

Future work will be to investigate a third comparison method, by comparing actual target points and tracker station locations, with the measurements and the fit result. Improving the non-linear least square algorithm by using weightings will be investigated. Furthermore, additional tests will be performed and the feasibility to calibrate a conventional bridge type CMM will be investigated.

7. ACKNOWLEDGEMENTS

The author thanks F van der Walt for helping with CMM and laser tracker measurements, the Mechatronic Engineering Department of the University of Stellenbosch and Prof. K Schreve, for supervising this project.

8. REFERENCES

[1] Benjamin B. Gallagher, "Optical shop applications for laser tracking metrology systems," Department of Optical Sciences, University of Arizona, 2003.

[2] T. Takatsuji, M. Goto, T. Kurosawa, and Y. Tanimura, "The first measurement of a three-dimensional coordinate by use of a laser tracking interferometer system based on trilateration," *Measurement Science and Technology*, vol. 9, pp. 38-41, 1998.

[3] M. Franke, J. Hannaford and H. Kunzmann H. Schwenke, "Error mapping of CMMs and machine tools by a single tracking interferometer," *CIRP Annals - Manufacturing Technology*, vol. 54, no. 1, pp. 475-478, 2005.

[4] Kam C Lau and Robert J Hocken, "Three and five axis laser tracking systems," Patent 1987.

[5] M. Vincze, JP Prenninger, and H. Gander, "A Laser Tracking System to Measure Position and Orientation of Robot End Effectors Under Motion," *The International Journal of Robotics Research*, vol. 13, p. 305, 1994.

[6] Antonietti N, Giugni A, Pisani M, and Zucco M, "Absolute Distance Meauserement with Sub-Fringe Resolution," in *International Conference on Space Optics*, Rhodes, Greece, 2010.

[7] Umetsu K, Furutani R, Takatsuji T, Osawa S, and Kurosawa T, "Calibration of a CMM using a laser tracking system," in *XVII IMEKO World Congress*, Dubrovnik, Croatia, 2003, pp. 1860-1863.

[8] EB Hughes, A Wilson, and GN Peggs, "Design of a High-Accuracy CMM Based on Multi-Lateration Techniques," *CIRP Annals - Manufacturing Technology*, vol. 49, pp. 391-394, 2000.

[9] GP Greeff, "A study for the development of a laser tracking system utilizing multilateration for high accuracy dimensional metrology," Stellenbosch University, Mechanical and Mechatronic Engineering Department, Master's Thesis 2010.

[10] P.D. Lin, C.H. Lu, and others, "Modeling and sensitivity analysis of laser tracking systems by skew-ray tracing method," *Journal of Manufacturing Science and Engineering*, vol. 127, p. 654, 2005.

[11] H. Zhuang and Z.S. Roth, "Modeling Gimbal Axis Misalignments and Mirror Center Offset in a Single-Beam Laser Tracking Measurement System," *The International Journal of Robotics Research*, vol. 14, p. 211, 1995.

[12] Shui H. Motaghedi, Zvi S. Roth and Ying Bai Hanqi Zhuang, "Calibration of multi-beam laser tracking systems," *Robotics and Computer-Integrated Manufacturing*, vol. 19, no. 4, pp. 301-314, August 2003 2003.

[13] G.X. Zhang et al., "A Study on the Optimal Design of Laser-based Multi-lateration Systems," *CIRP Annals - Manufacturing Technology*, vol. 52, pp. 427-430, 2003.

[14] Y. Bai, H. Zhuang, and ZS Roth, "Fuzzy logic control to suppress noises and coupling effects in a laser tracking system," *IEEE Transactions on Control Systems Technology*, vol. 13, pp. 113-121, 2005.

[15] T. Takatsuji, M. Goto, A. Kirita, T. Kurosawa, and Y. Tanimura, "The relationship between the measurement error and the arrangement of laser trackers in laser trilateration," *Measurement Science and Technology*, vol. 11, pp. 477-83, 2000.

[16] D. Zhang, S. Rolt, and P.G. Maropoulos, "Modelling and optimization of novel laser multilateration schemes for high-precision applications," *Measurement Science and Technology*, vol. 16, pp. 2541-2547, 2005.

[17] L. Guoxiong, Z. Zhen, L. Yongbing, "An improved cat's-eye retroreflector used in a laser tracking interferometer system," *Measurement Science and Technology*, vol. 14, no. 6, pp. 34-40, 2003.