A method of reconstructing the spatial measurement network by mobile measurement transmitter for shipbuilding

Siyang Guo¹, Jiarui Lin¹,², Linghui Yang¹, Yongjie Ren¹ and Yin Guo

¹ State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin, 300072, China

gsy135gsy@tju.edu.cn

Abstract. The workshop Measurement Position System (wMPS) is a distributed measurement system which is suitable for the large-scale metrology. However, there are some inevitable measurement problems in the shipbuilding industry, such as the restriction by obstacles and limited measurement range. To deal with these factors, this paper presents a method of reconstructing the spatial measurement network by mobile transmitter. A high-precision coordinate control network with more than six target points is established. The mobile measuring transmitter can be added into the measurement network using this coordinate control network with the spatial resection method. This method reconstructs the measurement network and broadens the measurement scope efficiently. To verify this method, two comparison experiments are designed with the laser tracker as the reference. The results demonstrate that the accuracy of point-to-point length is better than 0.4mm and the accuracy of coordinate measurement is better than 0.6mm.

1. Introduction

With the ongoing process of automation, large-scale metrology [1],[2],[3] plays a vital role in order to ensure product quality in the manufacturing industry. Especially in the shipbuilding industry, accurate and efficient measurement is necessary to provide the dimensional control for a quality product [4]. In traditional shipbuilding industry [5], the dimensional control method with angle square and gradienter is inefficient and inevitably brings the error caused by the human. Nowadays, lots of measurement systems have been applied in the shipbuilding industry, such as the total station [6] and photogrammetry [7]. However, the photogrammetry has limited measurement range which depends on the camera’s field of view, and the total station is not efficient with human collimation.

Recently, the distributed rotary-laser measurement system develops rapidly to accomplish an efficient and accurate three-dimensional coordinate measurement successfully. Take indoor GPS (iGPS) [8] as an example, it has been applied to ensure dimensional accuracy for the shipbuilding in South Korea and it provides an evaluation of the characteristics of ships [9]. Meanwhile, wMPS [10], based on the rotary-laser scanning, has achieved a great success in the large-scale metrology [11],[12]. So, wMPS with the advantages of high-precision and high-efficiency has a broad prospect for the shipbuilding.

The wMPS with multiple transmitters deployed around forms a spatial measurement network to fulfil measurement. The distributed nature makes this measurement network be easily influenced by the environment deeply [13]. For example, the environment of the shipbuilding industry is complex and harsh. Measurement with wMPS is challenged by limited measurement range as well as
obstructions of the complex structure which results in large measurement error or even the failure of measurement.

To solve the occlusion problem and ensure the accuracy of spatial measurement network for shipbuilding, this paper introduces a method of reconstructing spatial measurement network by mobile transmitter. The mobile transmitter moves in the measurement area and rapidly involves in the whole measurement network using target points by the spatial resection method. These target points are calibrated by the laser tracker beforehand. When finishing the measurement, this mobile transmitter can be deployed to other places. With the new transmitters joining in, the spatial measurement network is reconstructed and broadened without loss of accuracy. What’s more, the occlusion problem is solved with the reconstructed spatial measurement network in the shipbuilding factory.

In this paper, section 2 points out some measurement problems of wMPS faced in the measurement task for the shipbuilding. Section 3 gives a mathematical solution about how to reconstruct the measurement network. In section 4, based on the existing platform, experiences are designed to prove the accuracy and feasibility of this reconstructed measurement network. Finally in section 5, the conclusions of this proposed method are given and the improvement in the future is presented.

2. Description of reconstructing the spatial network for shipbuilding

These is a sketch map below to better figure out the environment in the shipbuilding industry. As the figure 1 shows, it is a part of the hull block assembly in the ship-building factory. The area is a rectangle about 12m*24m. The workpiece is very large and the aisles are just several meters wide. To achieve measurement, the wMPS is used. Four static transmitters are fixed in the corners of this area forming a measurement network. This measurement task has some problems:

1. There are some regions, shown in the figure 1 as “invisible area”, which can be seen by one fixed transmitter. So, the measurement can’t proceed.
2. Because of the diversity of the workpiece and the restriction by obstructions, no more than two transmitters can be seen at any place.
3. There are also some regions where the intersection angle of transmitters’ measuring signal is so large that the measurement condition is bad, like the part reading “large intersection angle “in the figure 1.

Above all, this measurement network can’t achieve the measurement either with high accuracy or with overall coverage.

![Figure 1. Description of the application with wMPS in the hull block assembly.](image)
In order to deal with these problems, the mobile transmitter is introduced into this system to reconstruct the spatial measurement network shown in figure 1. This mobile transmitter can add into the system quickly without recalibration with the scale bar and it can move to anywhere.

Firstly, in the region where two transmitters can’t be seen simultaneously, the mobile transmitter fulfils the measurement tasks with fixed transmitter. It can solve the problem of obstruction efficiently without loss of accuracy.

Secondly, the mobile transmitter can move and fulfil the measurement tasks with other two static transmitters. So, there are three transmitters measuring the coordinate together. The rotary-laser distributed system with three transmitters working together is the best compromise between accuracy and cost [8].

Thirdly, the layout of transmitters is always restricted by the obstruction and the size of the factory. In the large-scale factory, transmitters are often put far away from each other. So, the intersection angle of two static transmitters is random and often less than satisfactory. The mobile transmitter can be deployed to the measurement area in order to ensure that the intersection angle is at the optimum range.

Above all, the new method of reconstructing spatial measurement network is necessary.

3. Mathematical solution
There are two steps to reconstruct the spatial measurement network which are expounded below.

3.1 Establishment of high-precision coordinate control network
In the measurement area, some target points are fixed forming a high-precision coordinate control network, for example putting target points above the workpiece. Also, the target points need to be seen by most or even all of the static transmitters. The distance between coordinate control network and transmitter is less than the transmitter’s working distance.

To fulfil the spatial resection method, the target points need to be more than six points. And it’s necessary using laser tracker which is more accurate than wMPS to measure the coordinate of target points in the coordinate control network. According to the error analysis [14] of the laser tracker, the range accuracy is better than the angle measurement accuracy. So, based on the length constraint of laser tracker and bundle adjustment [15], a precise coordinate control network is established.

As shown in the figure 2, the laser tracker is put at different stations measuring all the target points respectively. The coordinates of target points are \((x_{ik}, y_{ik}, z_{ik})\) respectively, where \(i\) is the position number of laser tracker and \(k\) is the number of target points. It defines \(O-x_y_z\) as the coordinate system of the control network measured by the laser tracker when it is put in the first station.
position. With the common target points, the transformation relation between different laser tracker positions is obtained. To reduce the error of transformation, a model of rigid body kinematics [16] is used.

With these transformation matrixes and the target points’ coordinate in different laser tracker stations, the coordinates of the laser tracker in different positions can be transferred into one coordinate system, namely the \((x_i, y_i, z_i)\) where \(i\) is the position number of the laser tracker. There is an equation below which uses length constraint of the laser tracker to optimize the coordinate of target points.

\[
l_{ik}^2 = (x_{ik} - x_i)^2 + (y_{ik} - y_i)^2 + (z_{ik} - z_i)^2
\]  

where \(l_{ik}\) is the distance between target points and the laser tracker in the first position, \(k\) is the number of target points.

To solve this optimum equation, a nonlinear least square is introduced. Among many optimization algorithm, Levenberg-Marquardt algorithm (LM algorithm) is widely used [17],[18]. With the initial coordinate of each station \((x_i^0, y_i^0, z_i^0)\) and initial coordinates of target points \((x_{ik}^0, y_{ik}^0, z_{ik}^0)\), the coordinates of target points are optimized and the high-precision coordinate control network \(O−x,y,z\) is established with the final optimized coordinate. This coordinate control network is at least one order of magnitude more accurate than the wMPS and the final coordinates of target points are \((x_{ik}, y_{ik}, z_{ik})\).

3.2 Using the coordinate control network to rebuild the measurement network with spatial resection method

As shown in figure 3, there are three coordinate systems in the measurement system when adding the mobile transmitter into wMPS: the static transmitter’s coordinate system: \(O−x,y,z\) which is calibrated beforehand, the high-precision control network coordinate system: \(O−x,y,z\) which is established in the section 3.1 and the mobile transmitter coordinate system which is established in the mobile transmitter: \(O−x,y,z\). The procedure of adding the mobile transmitter to wMPS is to obtain the transformation relation from the mobile transmitter to the wMPS of static transmitters. If the coordinate of coordinate control network is measured by the measurement network of static transmitter, the transformation relation of these two coordinate systems is obtained.

Then, a method is introduced to obtain the transformation relation between the mobile transmitter coordinate system and control network coordinate system by spatial resection method. Put the mobile transmitter to the certain place and place receivers on the target points. According to the 3-D transformation, the transformation relation of coordinate is as followed:

\[
\begin{bmatrix}
 x_r \\
 y_r \\
 z_r
\end{bmatrix} = \begin{bmatrix}
 r_1 & r_2 & r_3 \\
 r_4 & r_5 & r_6 \\
 r_7 & r_8 & r_9
\end{bmatrix} \begin{bmatrix}
 x_{ik} \\
 y_{ik} \\
 z_{ik}
\end{bmatrix} + \begin{bmatrix}
 t_1 \\
 t_2 \\
 t_3
\end{bmatrix}
\]  

(2)

where \((x_{ik}, y_{ik}, z_{ik})\) is the coordinate of the target point in this control network coordinate system, \(k\) is the number of target points, \((x_r, y_r, z_r)\) is the coordinate of target points in mobile transmitter coordinate system, the rotation matrix \(R = \begin{bmatrix}
 r_1 & r_2 & r_3 \\
 r_4 & r_5 & r_6 \\
 r_7 & r_8 & r_9
\end{bmatrix}\), translation matrix \(T = \begin{bmatrix}
 t_1 \\
 t_2 \\
 t_3
\end{bmatrix}\).

When the mobile transmitter works, two laser planes of mobile transmitter pass by the receiver. Each equation of laser plane has been calibrated. The coordinate of receiver satisfies the planar equation below:
\[ a_{ii}x_i + b_{ii}y_i + c_{ii}z_i + d_{ii} = 0 \]  

(3)

where the \([a_{ii}, b_{ii}, c_{ii}, d_{ii}]\) is the parameter matrix of transmitters’ planar equations after rotation \([10]\), \(n\) is the number of transmitters, \(i\) is the planar equations’ number of one transmitter, and \([x_r, y_r, z_r]\) is the coordinate of receiver.

According to the equation 2 and 3, the relation can be established as a matrix format:

\[
AX = D
\]

(4)

where 

\[
A = \begin{bmatrix}
    a_{11}x_{11} & a_{11}y_{11} & a_{11}z_{11} & b_{11}x_{11} & b_{11}y_{11} & b_{11}z_{11} & c_{11}x_{11} & c_{11}y_{11} & c_{11}z_{11} & a_{12} & b_{12} & c_{12} \\
    a_{12}x_{12} & a_{12}y_{12} & a_{12}z_{12} & b_{12}x_{12} & b_{12}y_{12} & b_{12}z_{12} & c_{12}x_{12} & c_{12}y_{12} & c_{12}z_{12} & a_{13} & b_{13} & c_{13} \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    a_{1k}x_{ik} & a_{1k}y_{ik} & a_{1k}z_{ik} & b_{1k}x_{ik} & b_{1k}y_{ik} & b_{1k}z_{ik} & c_{1k}x_{ik} & c_{1k}y_{ik} & c_{1k}z_{ik} & a_{12} & b_{12} & c_{12} \\
\end{bmatrix}
\]

and 

\[
D = [-d_{11}, -d_{12}, \ldots, -d_{11}, -d_{12}]
\]

In the equation above, the rotation matrix and translation matrix are unknown and its parameter \(T_{11}, T_{12}, T_{13}, \ldots, T_{89}\) is to be calculated. Because of the error of two plane equations’ parameters and the coordinates of control network measured, there is no accurate value of the matrix \(X\) by the linear least-square algorithm. Also, the value of intercept \(d_{11}'\) or \(d_{12}'\) is so small that the matrix \(D\) is nearly a zero matrix. So, a preliminary calculation and nonlinear least-square algorithm is used to solve these equations accurately. In the following analysis, the incorrect value of the equation 5 is named as \(X_r\), the initial value of optimization algorithm is named as \(X_i\) and the exact solution of equation is named as \(X_e\).

Firstly, the incorrect value \(X_r\) of the equation \(AX = D\) is calculated by linear solution directly. The matrix \(D\) is nearly a zero matrix, so this is a homogeneous equation and there is a basic set of solutions. The initial value \(X_i\) of \(X\) has a fixed proportion with the basic set of solutions. Then, a compensation of ratio is to be done. According to the property of orthogonality of the rotation matrix, the parameters \(r_1, r_2, r_3\) satisfy the equation below:

\[
r_1^2 + r_2^2 + r_3^2 - 1 = 0
\]

(5)

So, the ratio can be got by the equation above and the initial value \(X_i\) of the optimization algorithm can be calculated by \(X_r\) multiplying the ratio.

Secondly, the nonlinear least-square method with Levenberg-Marquardt iterative method is to optimize the solution of the equation 5. The parameters of the rotation and translation matrix \(r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9, r_1, r_2, r_3\) satisfy the orthogonal constraints.

Finally, considering the strong restriction of orthogonal matrix, the penalty function is used to deal with these constraints. With the equation 4 and equation 7, the objective function can be written as below:

\[
E = \sum_{i=1}^{2} F_{ik}^2 + M \sum_{j=1}^{6} f_j^2 = \min
\]

(6)

where \(M\) is the penalty factor.

Above all, the accurate rotation and transition matrix can be calculated accurately and the mobile transmitter adds into the wMPS formed by static transmitters. The spatial measurement network is reconstructed by this mobile transmitter.

4. Experiments

4.1 Experiment platform set-up
To validate the feasibility and accuracy of reconstructed measurement network by the mobile transmitter of wMPS, two contrast experiments are designed to evaluate the performance of reconstructed measurement network. The first one is to validate the accuracy of point-to-point length measurement. The second one is to compare with the laser tracker in the coordinate measurement.

As shown in figure 4, two static transmitters and a mobile transmitter are prepared with its intrinsic parameters calibrated. One transmitter’s azimuth angular uncertainty [19] was about 2.4° (with the confidence probability of 99.73%). Two transmitters have formed a measurement network and a mobile transmitter is prepared to add into the network. Then, a new measurement network with only a static transmitter and a mobile transmitter forms, and it is called the new measurement network in the following passage. These experiments are to verify the feasibility and accuracy of this new measurement network. The coordinate control network is fixed on the roof and calibrated by the Leica AT901—LR laser tracker. About this laser tracker, the maximum permissible error (MPE) of the angular accuracy is ±15µm+6µm/m, and the MPE of interferometer accuracy is ±0.4µm+0.3 µm/m. The receiver of wMPS has the same size with the spherically mounted retroreflector (SMR) of the laser tracker in order to make a comparison.

![Figure 4. Platform of the proposed method](image)

**Figure 4. Platform of the proposed method**

**Figure 5. Point-to-point length measurement**

4.2 Verification of point-to-point length measurement

According to the Standards “ASME B89.4.19” [20] on dimensional metrology, the experiment of point-to-point length measurement test is designed. This experiment is to compare the point-to-point length measured by the new measurement network with a scale bar. This scale bar is calibrated by the laser tracker as the reference length. On both sides of the scale bar, there are spherical housings to place either a receiver or a SMR. When comparing the length, the scale bar is put about three kinds of attitudes, in the horizontal direction, in the vertical direction and in the depth direction. To improve the accuracy of this experiment, it performs ten times at each position, and has eliminated the gross error. The data is shown as figure 5:

As shown from the figure above, comparing with the laser tracker, the point-to-point length measurement error of the new measurement network in three directions is less than 0.4mm. The length error in the horizontal direction is less than the error of other directions. The accuracy of length measurement in each direction depends on either the accuracy of wMPS or the layout of coordinate control network, and the coordinate control network provides the strong constraints in space to ensure the accuracy of wMPS. In the figure 5, the length measured by the new measurement network is always less than the one measured by the laser tracker. It’s mainly because the receiver’s center of sphere is not at the same position with SMR.

4.3 Verification of coordinate measurement
The new measurement network is used for coordinate measurement, so the accuracy of coordinate measurement is necessary to ensure. In this experiment, the coordinate system of the proposed method is the same with the laser tracker coordinate system by coordinate transformation of some non-collinear common points. There are nine groups of coordinate to be compared in the space and each coordinate measures ten times at one place. The comparison results are listed in table 1.

| number | Coordinate measured by the laser tracker (mm) | Coordinate measured by the proposed method(mm) | Deviation\(a\) (mm) |
|--------|---------------------------------------------|-----------------------------------------------|---------------------|
|        | \(x_c\) \(y_c\) \(z_c\)                  | \(x_t\) \(y_t\) \(z_t\)                      | \(\Delta\)          |
| 1      | -3677.622 2991.999 1031.473                | -3677.62 2992.13 1031.34                      | 0.215               |
| 2      | -3667.079 3009.469 230.582                 | -3667.24 3009.34 230.33                       | 0.326               |
| 3      | -3661.098 3018.214 -570.162                | -3661.10 3017.69 -570.21                      | 0.527               |
| 4      | 2263.418 5616.739 -511.049                 | 2263.00 5617.12 -510.85                       | 0.599               |
| 5      | 2258.012 5605.601 297.892                 | 2257.65 5605.91 298.07                       | 0.508               |
| 6      | 2260.388 5593.652 1094.217                | 2260.49 5593.53 1094.07                       | 0.217               |
| 7      | -1251.391 6745.954 1645.435               | -1251.49 6745.74 1645.39                      | 0.240               |
| 8      | -2125.118 6383.763 1632.785               | -2125.27 6383.68 1632.71                      | 0.189               |
| 9      | -877.979 5752.818 -247.201                | -878.38 5752.85 -247.28                      | 0.410               |

\(a\) The deviation: \(\Delta = \sqrt{(x_t - x_c)^2 + (y_t - y_c)^2 + (z_t - z_c)^2}\)

As shown in table 1, the absolute position error of spatial coordinate measurement comparing with the laser tracker is less than 0.6mm. In fact, because of the instrumental error of the laser tracker and wMPS, the coordinate transformation method with common points inevitably induces some system error in the comparison experiment. Even though the error exists, this experiment still verifies the accuracy and feasibility of the proposed method.

5. Conclusions
A method of reconstructing spatial measurement network by mobile rotary-laser transmitter for shipbuilding is presented. This mobile transmitter can be placed flexibly in the measurement area so that it can adapt to various complex environments for shipbuilding and ensure measurement accuracy. With more than six target points, the mobile transmitter is able to add into the measurement network with the spatial resection method quickly and reconstruct the measurement network. Also, the establishment of precise coordinate control network with several target points is used to ensure the measurement accuracy of the optimized measurement network.

To prove the accuracy and feasibility of this reconstructed measurement network with mobile transmitter, two experiments are designed at a distance of five meters away from the transmitter. Comparing with the laser tracker, the result shows that the point-to-point length measurement accuracy in three directions is better than 0.4mm and the absolute positioning error is less than 0.6mm. Therefore, the spatial measurement network reconstruction method by mobile rotary-laser transmitter for shipbuilding is considered to be a feasible and efficient solution in large-scale complex environment.

With regard to this measurement network reconstruction for the complex environment by a mobile transmitter, more detailed work is to be improved in the future, such as combining inclinometer with the transmitter to restrict transmitter’s degree of freedom. In addition, to improve the accuracy of the measurement network, the combined adjustment is needed.

References
[1]. Estler, W. T., Edmundson, K. L., Peggs, G. N., & Parker, D. H. 2002 Large-scale metrology—an update. CIRP Annals-Manufacturing Technology, 51(2), 587-609.
[2]. Guan-yun, L. I. 2001 The State of the Art and Applications of the Industrial Measuring Systems.
Engineering of Surveying and Mapping, 2, 008.

[3]. Peggs, G. N., Maropoulos, P. G., Hughes, E. B., Forbes, A. B., Robson, S., Ziebart, M., & Muralikrishnan, B 2009 Recent developments in large-scale dimensional metrology. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 223(6), 571-595.

[4]. Peggs, G. N., Maropoulos, P. G., Hughes, E. B., Forbes, A. B., Robson, S., Ziebart, M., & Muralikrishnan, B. 2009 Portable Metrology and Dimensional Control in Integrated Shipbuilding Assembly Process. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 223(6), 571-595.

[5]. Huang F, Li W Y 2015 The application of total station hull block assembly. Marine Technology.

[6]. Kyle, S. A., Robson, S., Chapman, D. P., Cross, P. A., Iliffe, J. C., & Oldfield, S. 2001 Understanding Large Scale Metrology. Understanding Large Scale Metrology.

[7]. Koelman, H. J. 2010 Application of a photogrammetry-based system to measure and re-engineer ship hulls and ship parts: An industrial practices-based report. Computer-Aided Design, 42(8), 731-743.

[8]. Maisano, D. A., Jamshidi, J., Franceschini, F., Maropoulos, P. G., Mastrogiacomo, L., Mileham, A., & Owen, G 2008 Indoor GPS: system functionality and initial performance evaluation. International Journal of Manufacturing Research, 3(3), 335-349.

[9]. Park, J. T., Hayden, D. D., Kim, J. H., & Melendez, M. P. 2008 A New Methodology for the Evaluation of the Maneuvering Characteristics of Surface Ship Models. In ASME 2008 Fluids Engineering Division Summer Meeting collocated with the Heat Transfer, Energy Sustainability, and 3rd Energy Nanotechnology Conferences (pp. 393-398). American Society of Mechanical Engineers.

[10]. Zhao, Z., Zhu, J., Lin, J., Yang, L., Xue, B., & Xiong, Z. 2014 Transmitter parameter calibration of the workspace measurement and positioning system by using precise three-dimensional coordinate control network. Optical Engineering, 53(8), 084108-084108

[11]. Xue, B., Zhu, J., Zhao, Z., Wu, J., Liu, Z., & Wang, Q. 2014 Validation and mathematical model of workspace Measuring and Positioning System as an integrated metrology system for improving industrial robot positioning. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 228(3), 422-440.

[12]. Xue, B., Zhu, J., Yang, L., Zhao, Z., & Ye, S. 2014 The Application of the wMPS in Airplane Level Measurement. Photoelectric engineering, 41(8), 22-26.

[13]. Galetto, M., & Pralio, B. 2010 Optimal sensor positioning for large scale metrology applications. Precision Engineering, 34(3), 563-577.

[14]. JIN, Z. J., LI, J. X., YU, C. J., & KE, Y. L. 2015 Registration error analysis and evaluation in large-volume metrology system. Journal of Zhejiang University (Engineering Science), 4, 007.

[15]. Predmore, C. R. 2010 Bundle adjustment of multi-position measurements using the Mahalanobis distance. Precision engineering, 34(1), 113-123.

[16]. Geng, N., Zhu, J., Lao, D., & Ye, S. 2010 Theory and algorithm of coordinate system registration based on rigid body kinematics. Chinese Journal of Sensors and Actuators, 23(8), 1088-1092.

[17]. Ranganathan, A. 2004 The levenberg-marquardt algorithm. Tutorial on LM algorithm, 1-5.

[18]. Lourakis, M. I. 2005 A brief description of the Levenberg-Marquardt algorithm implemented by levmar. Foundation of Research and Technology, 4(1).

[19]. XIONG, Z., ZHU, J., GENG, L., REN, Y., YANG, X., & YE, S. 2012 Verification of angle measuring uncertainty for workspace Measuring and Positioning System. Chinese Journal of Sensors and Actuators, 2, 019.

[20]. American National Standards Institute. 2006 Performance Evaluation of Laser-based Spherical Coordinate Measurement Systems. American Society of Mechanical Engineers.
Acknowledgments
This work was funded by the National Natural Science Foundation of China (Grant No. 51405338, 51475329). The authors wish to express their sincere appreciation to editors and comments from the viewers would be appreciated very much.