A Contactless Measurement Instrument Based on Fusion of A Single-Point Laser Range Finder and A VIO System

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Abstract. To improve the safety and convenience of the traditional measurement instruments (such as Total station, Laser tracker), while reducing the system cost, a contactless measurement instrument consists of a single-point laser range finder (LRF) and a tracking module (a VIO system providing the measurement system 6DoF poses) is proposed in this paper. Its measuring procedure includes three steps: 1) Obtain the calibrated relative position parameters from a 3D position of the LRF. 2) Determine the remote target 3D point positions by fusing the measurement value of LRF. 3) In order to improve measurement accuracy, design a practical case-specific framework by analysing two typical measurement situations. This allows us to measure all scale factor information such as distance, height and clearance of a spatial structure in a convenient or portable way. Through the remote 3D point positions estimation experiment, the contactless measurement instrument exhibits the capability to satisfy the need of majority measurement applications for indoor architecture.

1. Introduction

Handheld LRF has been widely used in transmission and distribution measurement, industrial measurement acceptance, decoration design and so on. Some of those devices are developed for multifunction, like Bosch GLM80 [1], due to its integrated 360° incline sensor, which not only has the function of measuring the area and volume of an object, but also be able to sense indirect height by using the Pythagorean theorem. However, it is still very difficult or impossible to use the handheld LRF to get the definite coordinate position from remote space points and to determine the span between two remote objects. In many applications like construction, forestry, mining, and public works, the need to collect these reliable spatial and metadata is critical for almost all utility disciplines.

To satisfy those demands, theodolite, total station, and laser tracker are three commonly used measurement instruments in this field. Although those instruments can give high accuracy, they are a time-consuming and heavily experiences-relied procedures due to the difficulty of the setup for the initial measurement. Moreover, those instruments are very expensive ($20,000–$29,000).
Therefore, many research approaches are focusing on the handy contactless measurement problem. In [2], a spatial point target ranging system was proposed in our previous work. The system uses the combination of the laser ranging module and angle sensor module to measure the distance. The laser axis angle algorithm based on the triangle method is used to calculate measurement values between two arbitrary remote points. In [3], a remote measurement system consisting of a single-point LRF and an IMU was proposed. A movement of the system is estimated by using a strap-down inertial navigation algorithm. This movement information is combined with the distance sensor to obtain a remote point position. Unfortunately, it is difficult to perform sensor calibration and the position error of distance sensor increases due to the IMU drift error during motion time. So, the IMU is not ideal (suitable) for tracking 6DoF poses in this situation.

In this paper, we adopt a novel 6DoF pose estimation approach using a VIO system. The VIO system includes two parts: (1) The VIO hardware (intel realsense [4], mynt [5], zed2 [6]) which includes a set of stereo cameras and a hardware synched IMU. (2) The VIO algorithm (VINS [7], OKVIS [8], ROVIO [9]) which analyses the stereo images and fuses all sensor information together into 6DoF pose tracking. Because of the sensor fusion, VIO system has better performance for tracking 6DoF pose than traditional IMU odometry. Also, the calibration of single-point LRF and VIO is facilitated to operate, due to the calibration method of single-point LRF and camera is off-the-shelf.

In our method, the pose of the single-point LRF is determined by VIO system output pose and LRF-VIO calibration. And then a remote 3D point positions estimation method is adopted, in which the coordination of spatial points can be estimated by fusing the distance from the single-point LRF. Furthermore, a typical measurement case is investigated, and a practical case-specific methodology is proposed for three typical measurement scenarios.

2. The method of remote 3D point position estimation
In this section, a method is described, which is used to determine the position of the remote target 3D point. The proposed instrument consists of a VIO system and a single-point LRF. The 6DoF pose of VIO device is obtained from the algorithm of VIO system. The single-point LRF is used to provide the distance between a remote 3D point and the device. The pose of the single-point LRF is determined through a system calibration. Based on the pose and the measured distance provided by the single-point LRF, the coordinates of target points can be determined.

A pose of the single-point LRF consists of the following information: its translation vector \( t_l \) in the world coordinate system (WGS), and its rotation matrix \( R_l \) in the world coordinate system. In this paper, for convenience, a 6DoF pose information is represented by a transform matrix:

\[
T_l = \begin{bmatrix}
R_l & t_l \\
0^r & 1
\end{bmatrix} \in \mathbb{R}^{4 \times 4}, R_l \in SO(3), t_l \in \mathbb{R}^3
\] (1)

where, \( R_l \) is the rotation matrix of the single-point LRF, \( t_l \) is the translation vector of the single-point LRF.

The remote 3D point positions estimation method consists of the following steps:

**STEP1:** The normal VIO hardware includes a set of cameras/binocular-camera. Thence, the VIO system's parameters shall be set at first. These parameters include: (1) Built-in camera intrinsic and extrinsic parameters, those parameters will be used in Extrinsic calibration of a single-point LRF and VIO built-in camera; (2) Extrinsic parameters which is used to describe the transformation between the VIO tracking pose and the built-in right/left-eye camera \( T_{re,t} \). In general, these parameters are provided by the VIO manufacturer or developer. Therefore, the parameters are treated by their SDK (software development kit).

**STEP2:** A schematic diagram for the system calibration as shown in Figure 1. Many calibration methods [10-12] can be used to determine the camera's transform matrix \( T_{l,re} \). Then, by combining the previous parameters, the transform matrix (system calibration parameter) between LRF and VIO system \( T_{l,t} \) is obtained through the equation (2):

\[
T_{l,t} = T_{l,re} T_{re,t}
\] (2)
STEP1 and STEP2 only need to be done only once because the calibration parameters will never change if the LRF has been physically attached to the VIO system.

**Figure 1. Schematic Diagram for the Calibration of Measurement (VIO-LRF) Instrument**

**STEP3:** Estimation for positions of remote 3D points: We use Figure 2 to illustrate the procedure. When the instrument captures the remote point A in the 1st position, the pose from the VIO system $T_{t1}$ can also be obtained through VIO Algorithm at the same time. Combing the system calibration parameter $T_{st}$, the pose of the single-point LRF is then estimated through equation (3):

$$
T_{st} = \begin{bmatrix} R_{st} & t_{st} \\
0 & 1 \end{bmatrix} = T_{r,t}T_{t1}
$$

(3)

Simultaneously, the value of LRF $d_{t1}$ (the distance from the original point of LRF to the target point A) is measured. According to the equation (4), the spatial coordinate of the target point A $p_{A}(x,y,z)$ can be estimated:

$$
p_{A}(x,y,z) = R_{t1}[d_{t1} \ 0 \ 0]^{T} + t_{t1}
$$

(4)

**Figure 2. Schematic representation of remote 3D point positions estimation.**

Besides sensing the coordination of one point, the instrument also can be used to evaluate the relationship between two or multi-points. Assuming that the target points A, B, and C are in the same plane (this is the most common measurement condition), after the spatial coordination of target point, A is measured, the measurement instrument is moved smoothly to capture the spatial coordination of points B and C, respectively. With the positions (spatial coordination) of points A, B, and C, the relative
distance between each point, areas that these points are surrounding, and circumference of Polygons formed by the captured points. In figure 2, the distance between Points A and B is given by:

$$L_{AB} = \|p_A - p_B\|$$ (5)

The vertical distance between Points A and B is given by:

$$w_{AB} = \frac{[1 \ 0 \ 0]}{100} (p_A - p_B)$$ (6)

The horizontal distance between Points A and B is given by:

$$h_{AB} = \frac{[0 \ 1 \ 0]}{0.1} (p_A - p_B)$$ (7)

3. Experimental results and analysis

3.1. System overview and sensor calibration

In this section, the proposed measurement instrument (Figure 3) is used to perform experiments on remote 3D point positions estimation in three specific indoor substation measurement cases. The VIO system adopts the Intel RealSense Tracking Camera T265[4], it is a completely stand-alone solution that leverages state-of-the-art algorithms to output 6DoF tracking based on VIO algorithm, providing under 1% closed loop drift under intended use conditions. Laser range finder uses the MyAntenna L1s[13]. The measurement range is up to 40m, the sampling frequency 10Hz and the accuracy reads: \(\pm (1.5mm + \text{distance} \times 5\%)\). A picture of the experimental set-up is shown in Figure 3. T265 and MyAntenna L1s are connected to the NVIDIA TX2 embedded platform through a USB cable. All the modules are powered by a LiPo battery. Therefore, the proposed measurement instrument is convenient to be used in indoor or outdoor environments.

![Figure 3. Overview of the experimental set-up: (a) the portable experimental set-up; (b) the Measurement instrument. A 3D print bracket is used to rigidly attach the T265 and LRF.](image)

In calibration step, the built-in right eye camera is used to obtain the calibration parameters (Table 2). Using the Intel® RealSense™ SDK 2.0 to obtain the extrinsic parameter from "Gyro (output pose)" to "Right eye" \(T_{re,t}\). According to the Section 2-Step2, extrinsic calibration between the single-point LRF and the VIO system built-in right eye camera \(T_{lre}\) are obtained. Then, the transform matrix between single-point LRF (MyAntenna L1s) and VIO system(T265) \(T_{l,t} = T_{lre}T_{re,t}\) is calculated.

3.2. Remote 3D point positions estimation

The algorithm for remote 3D point positions estimation is applied to measure the triangle in Figure 4, the distance range between the experimental instrument and to be measured object is from 5m to 6m. The object is a triangle which is drawn on a white board. Three laser target plates are placed on each point the triangle as a ground truth to evaluate the accuracy of the proposed instrument. The distance
between these points is measured by the steel ruler, which is used as the ground truth in the experimental results, as shown in Table 1.

![Figure 4. The experimental setup for remote 3D point position estimation. The laser target plates on a white board as a ground truth.](image)

Table 1. Triangle measurement results

| No. | \(l_{ab}\) (cm) | \(l_{ac}\) (cm) | \(l_{bc}\) (cm) | \(h_{ab}\) (cm) | \(w_{ac}\) (cm) |
|-----|-----------------|-----------------|-----------------|-----------------|-----------------|
| Ground Truth | 100.0 | 100.0 | 120.0 | 80.0 | 60.0 |
| 1   | 99.67 | 100.12 | 120.13 | 80.09 | 59.88 |
| 2   | 100.34 | 99.87 | 119.89 | 79.89 | 60.13 |
| 3   | 100.85 | 99.45 | 119.65 | 79.76 | 60.56 |
| 4   | 99.12 | 100.78 | 120.67 | 80.91 | 60.63 |
| 5   | 98.93 | 97.97 | 121.27 | 79.03 | 61.12 |
| 6   | 101.21 | 101.54 | 119.14 | 81.07 | 59.27 |
| RMSE | 0.84955 | 1.11316 | 0.70153 | 0.70613 | 0.64924 |

In the worst case, the maximum of the root mean square of error in the table is 1.11316. The measurement accuracy can meet the need in almost measurement applications for indoor architecture [14-15].

4. Conclusion

This paper presents a contactless measurement instrument using a single-point LRF and a VIO system. Through the system calibration and the remote 3D point position estimation method, the coordination of remote 3D point can be determined. The system error analysis was conducted, and the results were shown in the error simulation experiment. A prototype of a measurement instrument has been assembled and tested. In a remote 3D point positions estimation experiment, the measurement accuracy is still able to meet the need of the most indoor architecture measurement application. Through the typical case experiments verified that the proposed contactless measurement instrument is able to be applied in acceptance testing for electric power engineering with satisfied accuracy, which indicates that this novel measurement method could replace the traditional one with the advantages of easier operation, less time and more economical. Our measurement instrument can be easily used as a handheld device, people can hold it and move freely instead of staying on one particular point.
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