AN INNOVATIVE INDOOR COORDINATE MEASURING SYSTEM FOR LARGE-SCALE METROLOGY BASED ON A DISTRIBUTED IR SENSOR NETWORK

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ABSTRACT

The aim of this paper is to describe the architecture and the working principles of a novel InfraRed (IR) optical-based distributed system, designed to perform low-cost indoor coordinate measurements of large-size objects. The hardware/software architecture and system functionalities are discussed, focusing the attention on the integration of methods for distributed network configuration, sensors self-calibration, 3D point localization, and data processing. A preliminary performance evaluation of the sensor devices as well as of the overall measuring system is carried out by discussing the experimental results obtained with a system prototype.

1. INTRODUCTION

In his 1978 survey paper on “Large-Scale Metrology” [1], Puttock observed that “the field of Large-Scale Metrology can be defined as the metrology of large machines and structures. The boundaries of this field will generally be confined to the metrology of objects in which the linear dimensions range from tens to hundreds of meters”. Then he concluded that “the field of Large-Scale Metrology is one which provides a significant challenge to the metrologist since virtually every project is different and, moreover, accuracy requirements are becoming more demanding”.

Several solutions based on different technologies have been proposed for metrology systems. At present, optical-based systems clearly demonstrate their advantages over the other approaches and their potentials for Large Scale Metrology applications. As noted by Estler et al. in a recent state-of-the-art update [2], tremendous improvements have been achieved in this field due to advancements in optical technology and fast, low-cost computation. However, it is recognized that significant technical challenges still remain “associated with high accuracy measurements of large structures”. Furthermore, most of these systems may not be cost-effective for measurements below a given level of accuracy.

Different classifications can be proposed for Large Scale Metrology instruments, based on the sensor layout (centralized or distributed systems) or the measurement operating conditions (contact or non-contact instruments). According to the working principles large scale metrology systems can be classified as ([3]):

- **Measuring systems that use two angles and one length.**  
  Most of the large-scale measuring systems rely on the determination of one length and two angles. In these systems the initial coordinates of a point are evaluated in a spherical coordinate system \((\rho, \varphi, \theta)\). For this reason these systems are also called Spherical Coordinate Measurement Systems (see Fig. 1). For each system, the angles are measured by means of angular encoders,
whilst the range measurement can be performed using either an interferometer like laser trackers or an ADM (Absolute Distance Measure) like laser radars and total stations, or a combination of both the two technologies like ADM enabled laser trackers [4][5]. The spherical coordinates are easily transformed in Cartesian coordinates by a central computing unit that is able to derive the measured object features from the points’ information.

**Measuring systems using multiple angles (triangulation).** Instead of using two angles and a distance measurement, it is possible to evaluate the position of a point in a three dimensional space using just angular information from two or more reference points. This working principle relies on very well known triangulation algorithms. Triangulation uses the known locations of two or more reference points, and the relative angles between the point to be localized and each reference point. In this case the unknown position of the point can be found by solving a linear system [6].

The camera-based triangulation system applies this principle. Three or more CCD (Charge Coupled Device) cameras are placed in known positions, for example fixed on a support. Each of them looks at a target determining the plane containing it. The position of the target is then univocally determined as the intersection of all the planes (see Fig 2).

Photogrammetry is another large-scale measurement technique based on angle measurements [7]. The principle is similar to that of camera-based triangulation, but, in this case, camera positions are not precalibrated, but they can be calculated afterwards together with the target position [8].

The working principle of the iGPS is also based on multiple angle measurements [9]. Knowing the horizontal and vertical angles from two or more transmitters, the system univocally determines the position of a probe [10]. In order to obtain accurate angle measurements the iGPS uses rotating laser beams.

This paper presents a novel optical-based distributed system (MScMS-IR – Mobile Spatial coordinate Measuring System InfraRed-based), designed to perform low-cost, simple, and rapid indoor coordinate measurements of large-sized objects. The novelty of the system is mainly related to its capabilities to extend the measurement domain, being able to cover large and geometrically complex working volumes by properly distributing the network sensors. In Section 2 the system architecture, the working principles of the basic units and their hardware/software relationships are outlined. Working principles are further described in Section 3 and Section 4, where system calibration and localization schemes are faced through algorithmic implementation. The
“pre-processing” tool for network visualization and layout optimization is presented in Section 5. The IR sensor network as well as the overall measuring system are, then, characterized by a set of experimental tests. The preliminary results, reported in Section 6, aim at evaluating measurement stability, repeatability, reproducibility and accuracy. Finally, Section 7 reports some concluding remarks and a brief outline of future research.

2. SYSTEM DESCRIPTION

The MScMS-IR is an indoor coordinate measuring system based on IR optical technology, designed for Large-Scale Metrology applications. The system, developed at the Industrial Metrology and Quality Engineering Laboratory of DISPEA – Politecnico di Torino, consists of three basic units (Fig. 4): a network (“constellation”) of wireless sensor devices, suitably distributed within the measurement volume, to estimate 3D coordinates of reflective passive markers; a mobile wireless and armless probe, equipped with two reflective markers, to “touch” the measurement points; a data-processing system, using Bluetooth connection, to acquire and elaborate data sent by each network node.

![Fig. 4: MScMS-IR (Mobile Spatial coordinate Measuring System InfraRed-based) architecture. The dashed lines represent visual links between sensor nodes and retro-reflective spheres (indicated as A and B) equipping the hand-held probe. The Bluetooth connection is established between each node and the processing system.](image)

A first prototype of MScMS exploited UltraSound (US) transceivers in order to communicate and evaluate mutual distances between the distributed sensor nodes and the hand-held probe [12]. The poor characteristics of US devices (non punctiform dimensions, speed of sound dependence on operating temperature, wave reflection and diffraction, etc.) caused a low accuracy in the measurement results [12][13]. To enhance system performance, current version implements an IR-based optical outside-in system, estimating the position of passive retro-reflective markers from their projections in different camera views.

2.1. Sensor network

The distributed network is based on a set of low-cost IR cameras, characterized by an interpolated resolution of 1024x768 pixels (native resolution is 128x96 pixels), a maximum sample rate of 100 Hz, and a viewing angle of approximately 45°. Each camera implements a real-time multi-object tracking engine, allowing to track up to four IR light sources. Each camera was coupled with a near-IR strobelight, consisting of a 160-chip LED array with a peak wavelength of 940 nm and a viewing half-angle of approximately 80°. Passive targets have been made by wrapping around polystyrene spheres a retro-reflective silver transfer film. Fig. 7 provides a virtual reconstruction of the working layout, with reference to a six cameras configuration. It has to be noted that the working volume consists of the volume of intersection of at least two viewing cones for reconstructing the spatial position of a single marker.

The marker dimensions depend on hardware capabilities and working volume. The IR sensor sensitivity has been experimentally evaluated by testing visibility distance of differently sized retro-reflective spheres. The implemented technology demonstrated to be able to track a 40 mm diameter marker at a maximum distance of 6 m.

The IR sensors configuration can be set according to shape and size of the measured object as well as of the working environment [11].

2.2. Measuring probe

The mobile probe (Fig. 5) consists of a rod ($l_r = 160$ mm), equipped with two reflective markers ($\phi = 40$ mm) at the extremes and a stick ($l_s = 64$ mm) at one end to physically “touch” the measurement points.

![Fig. 5: Mobile measuring probe.](image)

As the probe tip (V) lies on the same line of markers’ centers (A, B), spatial coordinates of point $X_t = (x_t, y_t, z_t)$ can be univocally determined by the following linear equation:

$$X_t = X_a + (X_b - X_a) \cdot t_t$$

where $X_a = (x_a, y_a, z_a)$ and $X_b = (x_b, y_b, z_b)$ identify the centers of marker A and B, respectively. The coefficient...
\[ t_r = \frac{X_r - X_i}{X_r - X_s} \]

is a priori known as it depends on probe geometry.

1.1. Data processing system

The data processing hardware consists of a 2.5 GHz computer platform, connected to IR cameras via a Bluetooth link. Each camera provides for the data processing system the 2D coordinates of the IR spot(s) in its view plane. As a matter of fact this saves the computational effort for performing the image analysis and spot coordinates identification by the computer platform. On the other hand, further improvement of the feature segmentation algorithm should increase stability of 3D point reconstruction. As cameras are sequentially sampled, image synchronization represents a critical issue for 3D reconstruction performance, depending on acquisition delays.

The processing software implements calibration, 3D point localization and data elaboration procedures (Fig. 6). The calibration algorithm takes as input from the camera embedded tracking engine the 2D position estimates of calibrated artifacts. It provides the camera positions and orientations in a user-defined coordinate reference system. These information are then used by the localization algorithm to perform 3D reconstruction of measurement points. Capabilities to perform single point coordinate measurements, distance measurements as well as geometry reconstruction are provided by the software tool. To this end, functions similar to those implemented by CMM commercial packages, have been integrated to support the user in elaborating the measurement data and reconstructing basic geometric features [14].

3. SYSTEM CALIBRATION

The multiple-camera calibration problem is faced by using an automated single-point self-calibration technique (Fig. 6) [15][16].

A single reflective marker is randomly moved within the working volume and tracked by the IR camera sensors. Image acquisition and processing are managed by the camera onboard hardware that directly provides pixel coordinates in the view plane. Modifications to the MATLAB calibration toolbox in [16] have been made to provide as input pixel coordinates instead of pixel images. An iterative pair-wise RANSAC analysis is used for discarding outliers [17]. The point cloud’s projective structure is computed by rank-4 factorization and refined through bundle adjustment. Finally, it is converted into Euclidean structures through Euclidean stratification [15]. The calibration software provides five intrinsic camera parameters (field of view, depth of field, resolution, focal length, and lens distortion) and six extrinsic camera parameters (3D coordinates of camera position and orientation angles).

A matrix transformation and a scaling are applied to transform the calibration coordinate frame in a user-defined reference frame. A laser cut aluminum square, measured to submillimeter accuracy by a Coordinate Measuring Machine, has been used as reference for calibrating the working volume.

4. LOCALIZATION ALGORITHM

Given a calibrated camera layout (i.e. \( n_c \) cameras, with their intrinsic and extrinsic parameters) and \( m \) markers, for each \( m \)-uple of 2D pixel coordinates \((u_j,v_j)\), with \( i = 1,\ldots,n_c \) and \( j = 1,\ldots,m \), the localization algorithm provides the 3D coordinates of the corresponding \( m \) retro-reflective markers (Fig. 6). As to the current implementation, a set of six cameras (\( n_c = 6 \)) has been used to recover the spatial coordinates of two markers (\( n_m = 2 \)) and to reconstruct the position of the contact point V.

Fig. 6: Scheme of the data processing system. The calibration procedure is responsible for determining positions and orientations of the IR sensors within the working environment. The localization procedure, implementing a triangulation method, reconstruct the 3D coordinates of the touched point by locating the passive markers on the measuring probe. A further step of data elaboration is implemented to coordinate the data processing operations (acquisition and elaboration), according to the measurement aim (single-point, distance or geometry reconstruction). In this operations, \( n \) is the number of measured points and \( n_p \) is the number of points needed to perform the processing.
Two main steps have to be followed for locating points:

1) find the correspondences among pixels in different image views,

2) match the 2D information of different camera views for recovering the spatial coordinates of the 3D point.

As to the first step, epipolar geometry, i.e. the intrinsic projective geometry between two views, has been used to correlate information from multiple camera images [18][19]. According to epipolar geometry principles, the correlation between two different image views of a point can be found by evaluating the distance between a 2D pixel \(X(u,v)\) in the first image and the epipolar line corresponding to the 2D pixel \(X(u,v)\) in the second image. The epipolar line corresponding to the point \(X(u,v)\) can be drawn through the fundamental matrix, i.e. the unique matrix \(F \in \mathbb{R}^{3 \times 3}\) which satisfies:

\[X'^T FX = 0\]

for all the corresponding points \(X \leftrightarrow X'\). The fundamental matrix can be computed according to the projection matrices of a given pair of cameras [19].

As the epipolar distance is proportional to the reprojection error after triangulation, large epipolar distances mean pixel correlation mismatches and large reprojection errors. Therefore, the correlation between pixel \(X_i(u_i,v_i)\) in the \(i\)-th camera view and pixel \(X_k(u_k,v_k)\) in the \(k\)-th camera view has been verified by applying the following threshold constraint:

\[X_i^T FX_k < \varepsilon\]

where \(F\) is the fundamental matrix of the pair consisting of the \(i\)-th camera and the \(k\)-th camera (with \(k \neq i\)), and \(\varepsilon\) is the user-defined threshold.

The concurrent presence of more than one retro-reflective marker within the working volume could give rise to some ambiguities in measurement point recovery. In some practical cases, probe positioning with respect to the IR sensor and its orientation could correspond to a very small distance between the two pixels in an image view. In order to reduce the errors in pixel correlation, a minimum search approach has been implemented. Stated that two pixels \(X_i(u_i,v_i)\) and \(X''_i(u''_i,v''_i)\) in the \(k\)-th camera view verified the threshold constraint with respect to epipolar line of point \(X_i(u_i,v_i)\) in the \(i\)-th camera view, the point \(X_i\) will be correlated to

\[W_i : W_i^T FX_i = \min \{X_i^T FX_i, X''_i^T FX_i\}\]

The second step of the localization algorithm deals with the triangulation problem. Given its 2D positions in different camera image planes \(X_i(u_i,v_i)\), with \(i = 1,..,n\) (\(n \geq 2\)), the 3D coordinates of a point \(Z(x,y,z)\) can be obtained through the following relationship:

\[
\begin{bmatrix}
  s_i \\
  t_i \\
  w_i
\end{bmatrix} = P_i \begin{bmatrix}
  x \\
  y \\
  z \\
  1
\end{bmatrix}
\]

where \([s_i \ t_i \ w_i]^T\) is the 2D pixel position in homogeneous coordinates and \(P_i\) is the projection matrix of the \(i\)-th camera obtained by the system calibration [15][16].

Gathering the 2D information from the \(n\) cameras (\(2 \leq n \leq n_i\) ) “seeing” the visible spot, the following system of \(2nx\) equations with three unknown variables \((x,y,z)\) can be written:

\[AZ - B = 0\]

where \(A \in \mathbb{R}^{2nx1}\) and \(B \in \mathbb{R}^{2nx1}\) are known matrices, whose elements are obtained as functions of projection matrices \(P_i\) and 2D pixel spatial coordinates \(X_i(u_i,v_i)\) [20]. The above equation is then solved for \(Z\) through a “linear” Single Value Decomposition method:

\[Z* = (A^T A)^{-1} A^T B\]

According to the vector of residuals \(E = (AZ* - B)\), a parameter \(e\), directly proportional to the overall variance, is estimated as [13]:

\[e \propto E^T E\]

This parameter is used as preliminary diagnostics in order to evaluate the correctness of 3D positioning. The obtained coordinates \(Z* (x,y,z)\) of the measured point, if characterized by high variance values, are automatically discarded according to a threshold method [13].

5. LAYOUT PRE-PROCESSING

A software tool for network positioning and visualization, based on the 3D content creation suite Blender [21], has been developed in order to graphically represent coverage capabilities of different sensor configurations and the effects of layout changes [22].

A Graphical User Interface (GUI) drives the user through the definition of the working setup and the analysis of network performance. As to the working setup, it consists of the physical working volume geometry, the measurement task definition and the network configuration. Data related to network layout are IR sensor coordinates and orientation angles, allowing to positioning cameras in the 3D virtual scene,
as well as the camera internal parameters (field of view, depth of field, resolution, focal length, and lens distortion). Since it is aimed at visualizing the results of algorithm-assisted as well as user-defined sensor positioning, the software allows loading by file as well as manual insertion and/or displacement of sensor nodes.

The “pre-processing” tool provides for the following features:

- coverage volume drawing: given a network layout, the volume covered by at least $n$ cameras is visualized;
- single point coverage: given a network layout and a set of $m$ measurement points, the coverage index (i.e. the number of cameras having the $j$-th point within their covered volume) is computed;
- measurement off-line simulation: given a network layout, a set of $m$ measurement points and the measuring probe geometry, the 3D point reprojection on each camera image plane is performed; operating conditions giving rise to possible ambiguities in 2D-3D reconstruction are reported as warnings.

A deployment strategy, based on genetic algorithms for optimal sensor placement, has been implemented and tested within a realistic working environment. Signal availability, minimization of reprojection errors due to ambiguities, and costs (in terms of number of network sensors) have been addressed as objectives of the optimization task, that is carried out prior to proceed to the sensor positioning. As a matter of fact, the objectives of the optimization are used as metrics for the “pre-processing” phase of the overall measurement procedure.

6. PRELIMINARY TESTS

A set of preliminary tests has been carried out to investigate the performance of the network of IR sensor devices as well as of the overall system, including the distributed sensor network, the hand-held measuring probe and the data processing system. It is noteworthy that the experimental results are strongly related to the network configuration, in terms of number of IR sensors, camera positioning and orientation. The data hereafter discussed have been obtained by using a set of six IR sensors, arranged in the working environment as shown in Fig. 7. The resulting measurement volume was about 2.0×2.0×2.0 m wide.

1.2. IR sensor network

The IR sensor network stability, intended as the property of the measuring instrument to provide 3D coordinates estimation constant in time [23], has been tested with respect to single point (spatial position of a single marker) as well as to distance measurements. Whereas it is intended as the dispersion of the estimated 3D coordinates, as to single point measurements, it refers to the reconstructed distance between two located markers for distance measurements. It has to be noted that, as to the results presented in this Section, the IR network stability includes components arising from hardware capabilities (affecting the 2D location of the spot in the camera projection plane through the sensor resolution capabilities) and software reliability (affecting the 3D point reconstruction through the multiple view correlation algorithm and the triangulation method).

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![Fig. 7: Virtual reconstruction of the working layout. The black wireframe represents the camera viewing cones, whereas the light grey wireframe represents the working volume (i.e. the volume of intersection of at least two cones).](image)

The single point stability has been evaluated by locating in static conditions a reflective marker in twelve different positions within the working volume. Marker coordinates over a time interval of 60 seconds for each static position have been acquired. Results, in terms of mean and standard deviation of the 3D coordinates, are reported in Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>$\bar{x}$ [mm]</th>
<th>$\bar{y}$ [mm]</th>
<th>$\bar{z}$ [mm]</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mm]</th>
<th>$\sigma_z$ [mm]</th>
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<tr>
<td>#1</td>
<td>613.10</td>
<td>1141.57</td>
<td>188.94</td>
<td>1.11</td>
<td>0.99</td>
<td>1.26</td>
</tr>
<tr>
<td>#2</td>
<td>918.74</td>
<td>907.60</td>
<td>539.35</td>
<td>0.69</td>
<td>0.50</td>
<td>0.33</td>
</tr>
<tr>
<td>#3</td>
<td>182.51</td>
<td>380.60</td>
<td>277.26</td>
<td>1.42</td>
<td>1.31</td>
<td>1.63</td>
</tr>
<tr>
<td>#4</td>
<td>1107.91</td>
<td>907.99</td>
<td>462.05</td>
<td>2.46</td>
<td>1.21</td>
<td>1.93</td>
</tr>
<tr>
<td>#5</td>
<td>558.98</td>
<td>790.83</td>
<td>670.02</td>
<td>0.42</td>
<td>0.40</td>
<td>0.43</td>
</tr>
<tr>
<td>#6</td>
<td>93.47</td>
<td>499.83</td>
<td>818.80</td>
<td>0.87</td>
<td>0.53</td>
<td>0.85</td>
</tr>
<tr>
<td>#7</td>
<td>855.55</td>
<td>694.15</td>
<td>462.05</td>
<td>2.46</td>
<td>1.21</td>
<td>1.93</td>
</tr>
<tr>
<td>#8</td>
<td>487.64</td>
<td>186.23</td>
<td>713.23</td>
<td>1.84</td>
<td>1.01</td>
<td>0.84</td>
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<tr>
<td>#9</td>
<td>347.20</td>
<td>1472.71</td>
<td>387.12</td>
<td>0.54</td>
<td>0.82</td>
<td>0.73</td>
</tr>
<tr>
<td>#10</td>
<td>532.38</td>
<td>926.63</td>
<td>325.53</td>
<td>1.62</td>
<td>0.86</td>
<td>1.53</td>
</tr>
<tr>
<td>#11</td>
<td>1208.37</td>
<td>897.55</td>
<td>421.22</td>
<td>5.08</td>
<td>1.49</td>
<td>3.10</td>
</tr>
<tr>
<td>#12</td>
<td>78.14</td>
<td>1033.12</td>
<td>544.50</td>
<td>0.96</td>
<td>0.60</td>
<td>0.90</td>
</tr>
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</table>

Tab. 1: Mean and standard deviation of static single point measurements.
It can be observed that the higher standard deviation values are encountered along the X and Z axes, for tests #4, #7, and #11, corresponding to critical positions within the working volume. The Y coordinate demonstrates better robustness capabilities: this could be ascribed to the reference network configuration used for these tests, as camera density is higher along the Y axis than along the other two axes.

The stability of distance measurements has been similarly evaluated by measuring a reference known distance, intended as the distance between two markers attached to a calibrated bar (nominal length: 408.17 mm), over a time interval of 60 seconds in static condition. Ten different positions and orientations of the calibrated bar have been randomly chosen within the working volume, for evaluating performance degradation due to positioning. Results, in terms of mean and standard deviation, are reported in Table 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Marker A (X_A, Y_A, Z_A) [mm]</th>
<th>Marker B (X_B, Y_B, Z_B) [mm]</th>
<th>ΔD [mm]</th>
<th>σD [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>713.67,890.45,77.91</td>
<td>329.43,751.09,68.10</td>
<td>408.87</td>
<td>1.54</td>
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<tr>
<td>#2</td>
<td>100.88,819.47,425.57</td>
<td>494.45,724.06,416.36</td>
<td>404.77</td>
<td>1.51</td>
</tr>
<tr>
<td>#3</td>
<td>533.18,880.48,918.41</td>
<td>923.03,776.19,929.22</td>
<td>403.70</td>
<td>0.45</td>
</tr>
<tr>
<td>#4</td>
<td>830.89,20.11,522.65</td>
<td>1106.81,316.22,537.97</td>
<td>404.64</td>
<td>0.92</td>
</tr>
<tr>
<td>#5</td>
<td>234.84,477.13,634.64</td>
<td>638.23,515.15,638.88</td>
<td>404.96</td>
<td>0.85</td>
</tr>
<tr>
<td>#6</td>
<td>573.09,917.95,716.82</td>
<td>924.15,1117.32,755.13</td>
<td>405.23</td>
<td>0.91</td>
</tr>
<tr>
<td>#7</td>
<td>993.34,733.69,208.67</td>
<td>1074.54,335.29,198.61</td>
<td>406.73</td>
<td>2.42</td>
</tr>
<tr>
<td>#8</td>
<td>581.68,937.28,268.79</td>
<td>190.37,817.94,272.34</td>
<td>408.93</td>
<td>1.58</td>
</tr>
<tr>
<td>#9</td>
<td>790.74,726.97,352.51</td>
<td>560.57,390.61,336.48</td>
<td>408.07</td>
<td>1.69</td>
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<tr>
<td>#10</td>
<td>494.38,977.89,723.48</td>
<td>319.91,1346.80,738.04</td>
<td>408.35</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Tab. 2: Mean and standard deviation of static distance measurements. Estimated position coordinates of marker A and marker B, equipping the measuring probe, are reported in the second and third column, respectively.

Stability performance are strictly related to the measurement technology, being affected by intrinsic parameters (camera resolution), operating constraints (camera vibrations), and measurement conditions (location of marker(s) within the working volume, relative position of marker(s) and cameras). Literature studies demonstrate that these orders of magnitude could be consistently reduced (until submillimeter accuracy) by improving sensor resolution [24],[25].

System accuracy has been preliminarily estimated by measuring a reference known distance (nominal length: 408.17 mm) several times (n = 12,340 samples) at different positions within the working volume. As shown in Fig. 8, the measurement error (intended as the difference between the measured distance and the nominal distance) shows a normal-like behavior, with a mean value μ = 5.2 mm and a standard deviation σr = 3.3 mm.

It is noteworthy that the shape and the parameters of the error distribution are strongly related to the position within the working volume and the acquisition procedure.

As a matter of fact, due to the camera positioning (approximately co-planar with respect to the ceiling), the distance reconstruction demonstrates a strong variation of the measurement error with the Z coordinate. On the other hand, as the distance measurements have been performed through dynamically acquired samples, system performances are affected by a worse image synchronization.

![Fig. 8: Accuracy test: measurement error (i.e. difference between the measured distance and the nominal distance) distribution.](image-url)

6.2. Overall system

The overall metrological system have been evaluated through repeatability and reproducibility tests and characterized by a preliminary estimation of the measurement accuracy.

Repeatability, i.e. “closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement” [23], has been tested both for single point and distance measurements. A single point within the working volume has been measured repeating the measurement k = 25 times, repositioning the probe in the same position for each measurement. Results referring to the reconstructed 3D positions of the probe tip V, according to the position estimates of the reflective markers A and B, are reported in Table 3.

It is noteworthy that repeatability characteristics are related to IR system stability in measuring a single point, as well as to probe geometry and human skills. Probe geometry could influence marker visibility during measurements and ambiguities in pixel correlation. On the other hand, human skills represent an external factor related to capabilities in holding the probe in a fixed position.

Measurement reproducibility, intended as “closeness of the agreement between the results of successive measurements of the same measurand carried out under changed conditions of measurement” [23], has been tested with reference to a single point. It has been evaluated by repeating the measurement of the same point with k = 25 different mobile probe orientations.
Table 3 reports statistical results of these preliminary tests. It can be noted that the standard deviation is basically higher for reproducibility tests. This behavior is strongly related to dependence of measurement accuracy on probe relative position and orientation with respect to the network devices.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mm]</th>
<th>$\sigma_z$ [mm]</th>
</tr>
</thead>
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<tr>
<td>repeatability</td>
<td>0.6</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>reproducibility</td>
<td>1.4</td>
<td>1.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Tab. 3: Standard deviation results for repeatability and reproducibility preliminary tests.

A preliminary evaluation of the overall system accuracy, intended as “closeness of agreement between a measured quantity value and a true quantity value of a measurand” [23], has been carried out with reference to a known distance $l_{\text{ref}} = 364.00$ mm. A set of $k = 590$ measured distances have been considered for analysis. The distribution of measurement errors (Fig. 9) shows a Gaussian-like behavior, with a mean value $\mu_e = 0.6$ mm and a standard deviation $\sigma_e = 0.8$ mm.

Fig. 9: Accuracy in distance measurement.

7. CONCLUSIONS

A low-cost optical IR-based system for indoor coordinate measurement of large-sized objects has been presented and preliminarily characterized through experimental testing. The system demonstrated to be portable and easy to setup, due to its modular architecture and to the exploitation of self-localization procedures for configuring the network independently on the working environment. Rapid measurements are provided by a robust image acquisition and processing system, at frequencies up to 100 Hz. According to its distributed-based architecture, the MScMS-IR system is able to extend its measurement capabilities to working environments characterized by large volumes and complex geometries.

The sensor device performance and the overall system capabilities in locating a single point as well as a 3D feature in a complex working volume have been evaluated. The preliminary results show a great potential of the system for its application in the field of Large-Scale Metrology. Specifically, system metrological characteristics can be improved by increasing the optical sensor resolution and sensitivity, for example, exploiting IR high-resolution cameras.

In a research perspective, a closer examination of factors affecting system performance, including IR hardware characteristics, self-calibration and localization algorithms, will be carried out. Further investigation should be devoted to the effects of the calibration and scaling procedures and to possible correction models for decreasing the average error. Experimental testing will be used for metrological analysis as well as for design of possible correction models, referring to testing procedures used for CMMs. Furthermore, methods for uncertainty propagation will be studied.

REFERENCES


