Accurate 3D measurement using optical depth information

A. Traumann, M. Daneshmand, S. Escalera and G. Anbarjafari

A novel three-dimensional measurement technique is proposed. The methodology consists in mapping from the screen coordinates reported by the system in the real world, and integrating distance gradients from the beginning to the end point, while also minimising the error through fitting pixel locations to a smooth curve. The results demonstrate accuracy of less than half a centimetre using Microsoft Kinect II.

Introduction: The problem of vision-based measurement calculation has been dealt with through different perspectives and methodologies in the literature. In what follows, a selection of the studies conducted in the foregoing field is briefly reviewed so as to provide a background to the approach proposed and implemented in this Letter. In [1], the focus is specifically on finding the range for mobile robots through DSP (digital signal processing) with the so-called 'binocular stereo vision'. The proposed methodology consists in capturing paired images of the target, along with Gaussian filter and improved Sobel kernels, and then determining its location through implementing feature-based local stereo matching. As the final stage, for alleviating mismatching possibilities, which would lead to more reliable performance, confidence, and left-right consistency filters are applied. Moreover, so as to achieve real-time control over the location detection algorithm, it is developed on the basis of a DSP/BIOS (basic input/output system) operating system. All in all, their suggested algorithm has claimed to be able to operate with more than 99% accuracy for point-to-point distance range of 120 cm within 39 ms in the worst case, which could be considered efficient and reliable.

The perception of body shape has been investigated from another perspective in [2], which deals with the disorders, such as anorexia and bulimia nervosa, caused, supposedly, by invalid perception of the body shape and sizes, being considered difficult to represent numerically. The foregoing study deems previous ones reported in the literature inadequate in the sense of properly illustrating the trend of the changes of the body shape while the level of fat is either increasing or decreasing. More precisely, the body shape does not vary in such a way that could be represented by simply stretching it in either of the directions consistently, as the one entitled 'distorting video technique (DVT)'; it rather demonstrates different amounts and types of changes in each part, i.e. the body part.

The main idea in the latter study is developing a home-based imaging system for automatic extraction of anthropometric body measurements. The work reported in [4] focuses on stereocopy, promoting a strategy helping to produce a visual illustration based on two separate images following method. The pixel locations are mapped to their corresponding real-world coordinates:

\[ f(x, y) = (X, Y, Z) \]  

where \( x, y \in \mathbb{N} \) are the screen coordinates and \( X, Y, Z \in \mathbb{R} \) are the corresponding real-world coordinates.

For each measurement two points of screen coordinates are required: a starting and an ending point, let us denote the starting point by \( P_s \) and the ending point by \( P_e \). These two points are obtained from the user input. The most obvious measurement can be performed by finding the Euclidean distance between the real-world points corresponding to these two points:

\[ d(P_s, P_e) = \| f(P_s) - f(P_e) \| \]  

This distance is rarely correct; however, as the real distance depends on the nature of the surface between these two points, the Euclidean distance would be correct only when the path from start to end along the surface is a completely straight line. In reality, the distance should be given by the following line integral:

\[ d(P_s, P_e) = \int_C h(X, Y) ds \]  

where \( C \) is the geodesic path from \( f(P_s) \) to \( f(P_e) \) that is obtained by projecting the line segment \( P_sP_e \) on the real-world coordinate surface, and \( h : \mathbb{R}^2 \rightarrow \mathbb{R} \) is a function that gives the \( Z \) coordinate of the projected path at the surface point \((X, Y)\).

The proposed algorithm approximates the true distance using the following method. The pixel locations are mapped to their corresponding real-world coordinates. This situation can be represented by a weighted graph where each node is connected to four nodes that were created based on the real-world coordinates obtained by mapping the neighbouring pixel locations to real-world coordinate space.

The main contribution of this Letter arises from the fact that, instead of measuring 3D geodesic paths, as performed in [7], the shortest path is computed by considering only \( X \) and \( Y \) coordinates, which, from the mathematical point of view, means that the graph where the Dijkstra’s algorithm [8] is applied is constructed as \( \sqrt{(X_1 - X)^2 + (Y_1 - Y)^2} \), whereas the Euclidean distance would be \( \sqrt{(X_1 - X)^2 + (Y_1 - Y)^2 + (Z_1 - Z)^2} \). More clearly, the underlying notion is that the path obtained via the approach suggested in this Letter is more realistic in the sense that it is the result of projecting the path connecting the beginning and end points onto the surface, and involves overcoming variability of the possible appearance of the hand due to the high flexibility of the hand, especially at the wrist part. The underlying assumption, which has been verified through conducting several experiments, is that the hand landmarks are always located in certain positions with constant geodesic distances from an anatomical reference point, which is also automatically detected. The methodology consists in segmenting the human body on the basis of the depth information and afterwards obtaining a graph representation including the geodesic paths originating from the aforementioned reference point, \( G = (V, E) \), where \( V = \mathbb{B} \) denotes the vertices, and \( E \subseteq V \times V \) stands for the edges, such that

\[ E = \{ (p, p') \in V \times V : \| (i, j, k) - (i', j', k') \|_2 < 1 \} \]  

It should be noted that in the above formulation, \( \| \cdot \| \) returns the infinity norm of its vector component, and \( (i, j, k) \) and \( (i', j', k') \) denote the 3D coordinates of the points \( p \) and \( p' \), respectively, in \( \mathbb{B} \), which, if being neighbours, are connected with the edge \( e = (p, p') \in E \), corresponding to the weight \( w(e) = \| p - p' \| \), on which basis, the geodesic distance between the two points is defined as follows:

\[ d_e(p, p') = \sum_{e \in E(p, p')} w(e) \]  

which includes the edges along the shortest path between the points, determined based on the min-path Dijkstra’s algorithm [8].

Proposed method: The proposed method requires a coordinate mapping from screen coordinates to real-world coordinates. It can be achieved in various ways: it is possible to use a depth camera that provides the mapping, or it can be obtained from finds of 3D reconstruction method based on stereo vision, structured lighting etc. From here on, it is assumed that there exists a function \( f : \mathbb{N}^2 \rightarrow \mathbb{R}^3 \) that maps screen coordinates to real-world coordinates:

\[ f(x, y) = (X, Y, Z) \]  

\[ x, y \in \mathbb{N} \]
rather than simply considering a straight line drawn between them, which is tantamount to excluding the Z-coordinate values from the calculations and avoiding bypassing the convexities and concavities constructing the actual surface.

After obtaining the path, the algorithm starts to iterate through the path and sums up the total Euclidean distance between all the iterated points. Let \( p_k \) denote the \( k \)th visited point. The Euclidean distance from \( p_{k-1} \) to \( p_k \) is added to a total sum of distances \( D \). After iterating all the pixels the total sum \( D \) is a close approximation of the real distance. The described approximation can be written as

\[
D = \sum_{k=1}^{m} \| p_{k-1} - p_k \|
\]  

where \( m \) denotes the total number of visited points. The described method works by following the approximate path between the starting and the ending points. The path is then divided into several smaller parts; each of those smaller parts is approximated using the Euclidean distance. The final output of the algorithm is achieved by summing up all the lengths of the smaller path segments.

**Results:** The proposed method was tested in several scenarios, one of which was a large ball with marks on it, as shown in Fig. 1, and some others are illustrated in Fig. 2. In the former, there are four points marked on the ball and measurements were performed between all of them. We refer to these four points by \( A, B, C, \) and \( D \).

The results of the automatic measurements using the proposed algorithm are compared with the measurements obtained by manual measurements using a measuring tape. These results are shown in Table 1.

<table>
<thead>
<tr>
<th>Points</th>
<th>Proposed method (cm)</th>
<th>Manual measurement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>20.87979</td>
<td>20.7</td>
</tr>
<tr>
<td>AC</td>
<td>37.34988</td>
<td>37.2</td>
</tr>
<tr>
<td>AD</td>
<td>28.36199</td>
<td>28.0</td>
</tr>
<tr>
<td>BC</td>
<td>16.28063</td>
<td>16.2</td>
</tr>
<tr>
<td>BD</td>
<td>19.71188</td>
<td>19.3</td>
</tr>
<tr>
<td>CD</td>
<td>24.80985</td>
<td>24.6</td>
</tr>
</tbody>
</table>

It can be seen that the measurement results of the proposed method are very accurate and are close to the results that were obtained manually. The maximum difference was only 0.41 cm, while the average difference was 0.23 cm. On average, the accuracy of the proposed automatic measurement for different scenarios is 0.25 cm, as shown in Fig. 1. Hence, it is concluded that the proposed method can be used to measure distances along surfaces with high accuracy.

**Conclusion:** In this Letter, a novel 3D measurement technique has been proposed. The proposed algorithm maps the screen coordinates to the real-world coordinate and then integrates distance gradients from the beginning to the end point. The error of fitting pixel locations to a smooth curve is also minimised. The conducted experimental results show an accuracy of less than half a centimetre for the proposed technique.

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One or more of the Figures in this Letter are available in colour online.

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**References**