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ACCURACY AND ERROR STUDY OF HORIZONTAL AND VERTICAL MEASUREMENTS WITH SINGLE VIEW METROLOGY FOR ROAD SURVEYING

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ABSTRACT

High quality digital image can be produced and stored with cost effective embedded system, thanks to advancement of low power digital camera and hardware accelerated high definition video image compression System-on-Chip. Image recorded with these multi-megapixel digital cameras allowed the world to be digitized more accurately (compared with conventional VGA camera with low resolution) and hence enable the use of single image as the metrology tool. Using the single view geometry techniques (planar homography, vanishing points and vanishing lines) widely accepted by the community, the suitability of applying these techniques with error reduced for road surveying is studied and reported in this work.

Keywords: planar homography, homogenous estimation method, singular value decomposition, single view height measurement, single view metrology.

INTRODUCTION

The cost of megapixel digital camera has dropped significantly along with the flourish of low cost smartphone in the market. The size of the object inside a taken image (single view) can be measured up to a scale, with respect to a reference object in the image, if the actual size/metric of the reference object is not known. With some known geometry information, e.g. the object is standing perpendicular to the floor or plane to plane transformation between camera image plane with respect to a plane in the image [1], the size of the object can then be measured in metric. A pre-calibrated camera mounting rigidly on the rooftop of a survey vehicle, with proper pre-calibration and the use of single view geometry, will allow the road survey team to collect and measure the road geometry (e.g. width of lane, the horizontal measurement) as well as roadside inventory (e.g. height of the sign board, the vertical measurement) [2] with cost effective digital camera.

The content of this paper is organized as follow. The single view geometry method used by the photogrammetry community to produce accurate horizontal and vertical measurement is firstly reviewed in Section 2 and Section 3, respectively. Using the implemented single view geometry method, outdoor image is captured by the camera mounted on the rooftop of the survey vehicle, the result of measurements are reported and discussed in Section 4. The suitability of applying single view geometry for road survey study is then summarized at the end of this paper.

HORIZONTAL OBJECT MEASUREMENT WITH HOMOGENOUS ESTIMATION METHOD AND SINGULAR VALUE DECOMPOSITON (SVD)

The image produced by a pin-hole camera can be modelled as the projection of object in 3D world into a 2D image plane. The projection of a planar object (e.g. the road surface) in 3D world into the 2D image plane can be described by a planar homography H [3] (matrix with dimension 3x3) as

$$\underbrace{\begin{bmatrix} u \\ v \\ 1 \end{bmatrix}}_{:=m} = \underbrace{\begin{bmatrix} \mathrm{h}_{11} & \mathrm{h}_{12} & \mathrm{h}_{13} \\ \mathrm{h}_{21} & \mathrm{h}_{22} & \mathrm{h}_{23} \\ \mathrm{h}_{31} & \mathrm{h}_{32} & \mathrm{h}_{33} \end{bmatrix}}_{:=H} \underbrace{\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}}_{:=M} \quad (1)$$

where m is the pixel coordinate on the camera image plane and M is the grid coordinate of the 3D planar object [4].

From (2), each image to world point correspondence provides two equations which are linear in the 2 matrix elements.

$$\begin{aligned} h_{11}u + h_{12}v + h_{13} &= h_{31}xX + h_{32}yX + h_{33}X \\ h_{21}u + h_{22}v + h_{23} &= h_{31}xY + h_{32}yY + h_{33}Y \end{aligned} \quad (2)$$

For n correspondences a system of $2n$ equations, F_{2nx9}, is obtained (see equation 3). If $n = 4$, then an exact solution is obtained. Otherwise, if $n > 4$, the matrix is over determined and the solution can be estimated by a suitable minimization scheme. The solution, planar homography describing the plane to plane projection, can be resolved up to the scale factor by employing the concept of least square error [5] as

$$\underbrace{\begin{bmatrix} X_1 & Y_1 & 1 & 0 & 0 & 0 & -u'_1X_1 & -u'_1Y_1 & -u'_1 \\ 0 & 0 & 0 & X_1 & Y_1 & 1 & -v'_1X_1 & -v'_1Y_1 & -v'_1 \\ X_2 & Y_2 & 1 & 0 & 0 & 0 & -u'_2X_2 & -u'_2Y_2 & -u'_2 \\ 0 & 0 & 0 & X_2 & Y_2 & 1 & -v'_2X_2 & -v'_2Y_2 & -v'_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X_n & Y_n & 1 & 0 & 0 & 0 & -u'_nX_n & -u'_nY_n & -u'_n \\ 0 & 0 & 0 & X_n & Y_n & 1 & -v'_nX_n & -v'_nY_n & -v'_n \end{bmatrix}}_{F} \begin{bmatrix} h_{11} \\ h_{12} \\ \vdots \\ h_{32} \\ h_{33} \end{bmatrix} = \begin{bmatrix} \epsilon'_{11} \\ \epsilon'_{12} \\ \vdots \\ \epsilon'_{n1} \\ \epsilon'_{n2} \end{bmatrix} \quad (3)$$

where X_i and Y_i is the grid coordinate of the 3D planar object and u'_i and v'_i is the image pixel coordinate of the 2D image plane of correspondence i.

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If $n > 4$, the unknowns found from the number of correspondences, n will be more than 8. Therefore, SVD is applied to decompose A into three matrices, UDV^T

$$F^T F = A = UDV^T \quad (4)$$

The diagonal entries of the diagonal matrix D, σ_i, are known as the singular values of A [6].

The eigenvector that is corresponding to the minimum eigenvalue located on D will be the optimized solution of the system. With large amount of correspondences will provide higher accuracy of H.

Once the value of planar homography is resolved, the distance between any two points ([X_{p1}, Y_{p1}],[X_{p2}, Y_{p2}]) lying on the 2D image plane can be measured as

$$d = \sqrt{(Xp1 - Xp2)^2 + (Yp1 - Yp2)^2} \quad (5)$$

From (1), where

$$\begin{bmatrix} X_{pi} \\ Y_{pi} \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}^{-1} \begin{bmatrix} u_{pi} \\ v_{pi} \\ 1 \end{bmatrix} \quad (6)$$

Single view height measurement with different number of reference objects

The height of an object, the distance representing the top and bottom of an object perpendicular to the floor, can be measured with using only one image as proposed by A. Criminisis in his work [7]. The method proposed by A. Criminisis required the use of multiple vanishing points and vanishing line, derived from the real-world geometry information in the image, to firstly define the floor where the object is standing (see Figure-1). The ability to accurately determine the vanishing point and vanishing line directly affect the result and error of the height/vertical measurement.

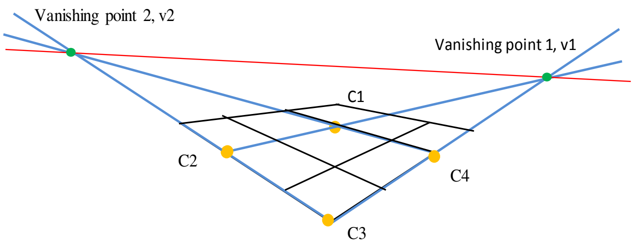

Figure-1. The corners (orange dots, c_1 to c_4), representing a plan on the foor, is used to find the vanishing points (green dots) and the vanishing line, l (red line).

The vanishing point or line can be determined by using cross product:

$$\begin{aligned} c_2 \times c_1 &= l_1 \\ c_3 \times c_4 &= l_2 \\ c_4 \times c_1 &= l_3 \\ c_3 \times c_2 &= l_4 \\ l_1 \times l_2 &= v_1 \\ l_3 \times l_4 &= v_2 \\ v_3 \times v_4 &= l_v \end{aligned} \quad (7)$$

The cross product of two coordinates, c on the grid will form a line. These lines will have vanishing points, v_n and the line (red line in Figure-1) passes through both the v_n called vanishing line.

In the single view height measurement [8], each of the objects with known height can be used as the reference height, Z_{rn} to help determine the scale factor ratio, α before the height of the target object (distance between t_z and b_z) is measured. The height of the target object measured under the help of the vertical vanishing point, v_v which is the intersection point for the dotted lines formed by $(b_{rn} \times t_{rn}) \times (b_z \times t_z)$ as shown in Figure-2.

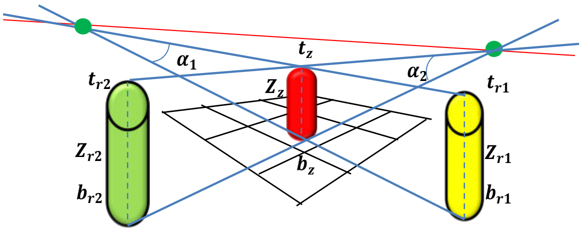

Figure-2. The top point (t_{rn}) and the bottom point (b_{rn}) of the reference object (yellow or green cylinder) forming a line (dotted line) which is parallel with the line formed by the t_z and b_z for the target (red cylinder).

For the height measurement with one reference object, α can be determined with equation:

$$\alpha = -\frac{\|b_r \times t_r\|}{Z_r(l_v \cdot b_r)\|v_v \times t_r\|} \quad (8)$$

After α is determined, the height of the target object, Z_z, can be estimated with (9):

$$Z_z = -\frac{\|b_z \times t_z\|}{\alpha(l_v \cdot b_z)\|v_v \times t_z\|} \quad (9)$$

The height of the target object can be estimated more accurately with the use of multi reference objects with known height [7]. Re-arranging (8)

$$\alpha Z_{rn}(l_v \cdot b_{rn})\|v_v \times t_{rn}\| = -\|b_{rn} \times t_{rn}\| \quad (10)$$

With n reference objects with known height in the image, a $n \times 2$ matrix, A will be:

$$A = \begin{bmatrix} Z_{r1}(l_v \cdot b_{r1})\|v_v \times t_{r1}\| & \|b_{r1} \times t_{r1}\| \\ \vdots & \vdots \\ Z_{rn}(l_v \cdot b_{rn})\|v_v \times t_{rn}\| & \|b_{rn} \times t_{rn}\| \end{bmatrix} \quad (11)$$

where n is the number of reference height.

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For $n = 1$, then $As = 0$ where $s = (s_1 \quad s_2)^T$ is a homogeneous 2-vector and

$$\alpha = \frac{s_1}{s_2} \tag{12}$$

For case $n > 1$, the solution s can be determined by finding the eigenvector that is corresponding to the minimum eigenvalue of A^T. The α estimated with multiple reference objects can be determined by (12).

EXPERIMENTAL RESULTS

Using the methods as discussed in Section 3, an outdoor experiment is setup to validate the implemented horizontal and vertical measurement system. A camera is mounted on the rooftop of a survey vehicle with the camera focus plane around 10 meters from the camera (see Figure-3). The obtained results are discussed in the following section.

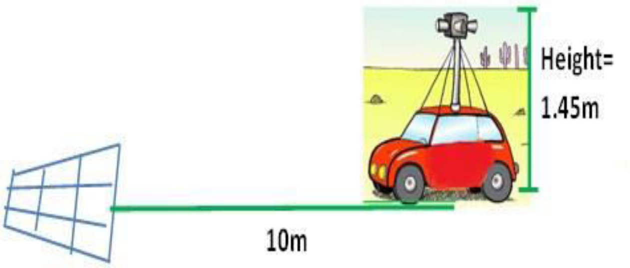

Figure-3. The distance of the measured region is 10 meters from the camera setup on the road survey vehicle and the height of the camera from the ground plane is 1.45m

Results for horizontal measurement

Horizontal object measurement had been taken after the camera calibration method with the 3×3 grid created by connects 24 pipes together. All the 24 pipes had been labelled with number from 1 to 24 and each of them is 1.20m. (see Figure-4 and 5).

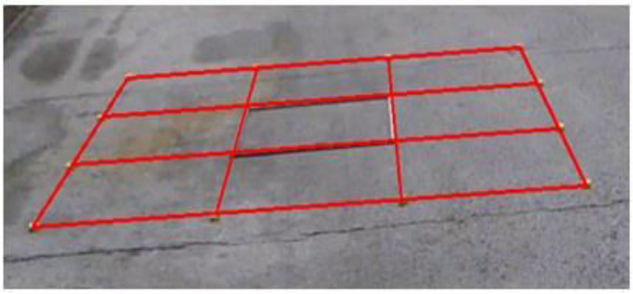

Figure-4. The combination of the pipes form a 3 x 3 grid.

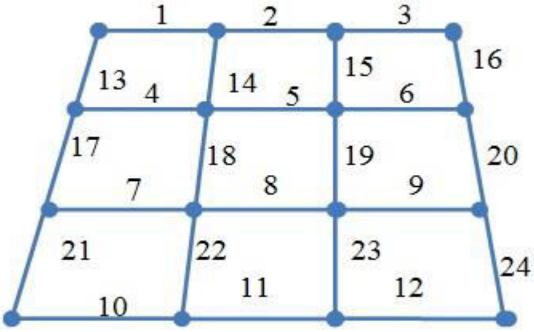

Figure-5. The pipes labelled from 1 to 24.

Table-1. The length of the pipes estimated for the accuracy study of the system.

Pipe	Measured Value(meter)	Pipe	Measured Value(meter)
1	1.196	13	1.221
2	1.216	14	1.224
3	1.220	15	1.189
4	1.185	16	1.185
5	1.194	17	1.208
6	1.208	18	1.210
7	1.199	19	1.193
8	1.211	20	1.189
9	1.219	21	1.219
10	1.203	22	1.215
11	1.221	23	1.209
12	1.200	24	1.212
Mean obtained from 24 pipes			1.206
Standard deviation obtained from 24 pipes			0.012

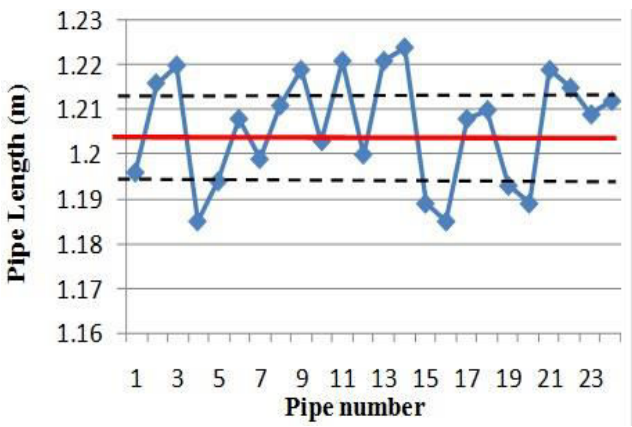

Figure-6. Length of pipe measured for each pipe (the red horizontal straight line represents the mean value = 1.206m and the standard deviation = 0.012m).

Observation: The average of the output obtained is 1.206 ± 0.012m. Compared with the actual length of the pipe, the difference of the mean value optimized to the error of 0.006m (0.5%). It shows that the implemented horizontal measurement method can be used to provide accurate horizontal measurement.

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Results for single view height measurement

For the single view height measurement, three objects (0.33m height, 0.20m width) had been set up as shown in Figure-7. The left hand edge and right hand edge of each of the objects is labeled (*a*, *b*, *c*, *d*, *e*, *f*) and measured (see Appendix A for the selected image coordinates to produce the measurement). The location of the reference object with respect to the result of measurement is firstly discussed. The number of reference objects with respect to the accuracy of the measurement is discussed at the end of this section.

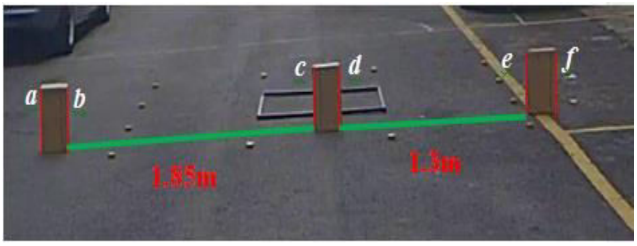

Figure-7. Experiment setup (3 objects, 0.33m height, 0.20m width) for vertical measurement. The distance between edge *a* and *f* is 3.75m.

Effect of the location of the reference object with respect to the result of measurement

The results of single reference height measurement with the labeled edges are shown in Table-2. It is obvious that the accuracy of height measurement decrease with respect to the increasing of the distance of the target from reference object (e.g. for target edge *f*, more error is reported when the left most edges are used as the reference edge).

Table-2. Height measurement (Edge *a*, *b*, *c*, *d*, *e*, *f*, 0.33 meter) with only single reference object.

Target edge	Result of measurement (meter) based on different location of the reference edge (error is reported at the bottom of the measurement)					
	Reference edge					
	a	*b*	*c*	*d*	*e*	*f*
a		0.3294 (-0.0006)	0.3201 (-0.0099)	0.3222 (-0.0078)	*0.3191* *(-0.0109)*	*0.3199* *(-0.0101)*
b	0.3344 (+0.0044)		*0.3217* *(-0.0083)*	*0.3352* (+0.0052)	*0.3226* *(-0.0074)*	0.3231 (-0.0069)
c	*0.3369* *(+0.0069)*	0.3289 (-0.0011)		0.3281 (-0.0019)	*0.3256* *(-0.0044)*	0.3341 (+0.0041)
d	*0.3380* *(+0.0080)*	*0.3215* *(-0.0085)*	0.3292 (-0.0008)		0.3321 (+0.0021)	0.3243 (-0.0057)
e	*0.3421* *(+0.0121)*	*0.3204* *(-0.0096)*	0.3208 (-0.0092)	0.3337 (+0.0037)		0.3283 (-0.0017)
f	*0.3440* *(+0.0140)*	*0.3391* *(+0.0091)*	0.3253 (-0.0047)	0.3358 (+0.0058)	0.3291 (-0.0009)	

Effect of the multiple reference objects used with respect to the accuracy of the measurement

The second experiment is conducted by using up to four reference edges to measure the height of the target edge. Edges for the other two objects, beside the target object, will be used as the reference heights for the measurement (*e.g.*, edge *c*, *d*, *e* and *f* are used as the references height to measure edge *b*. The measurement result, with respect to the number of reference object height used is shown in Table-3.

Table-3. The measurement with multiple reference objects.

Target edge	Number of reference objects used and the respective measurement result in meter (edges used to produce the measurement)			
	1	2	3	4
a	0.3326 (*e*) (+0.0026)	0.3284 (*c*, *f*) (-0.0016)	0.3290 (*c*, *e*, *f*) (-0.0010)	0.3322 (*c*, *d*, *e*, *f*) (+0.0022)
b	0.3199 (*d*) (-0.0101)	0.3294 (*c*, *f*) (-0.0006)	0.3335 (*c*, *e*, *f*) (+0.0035)	0.3348 (*c*, *d*, *e*, *f*) (+0.0048)
c	0.3378 (*b*) (+0.0078)	0.3325 (*e*, *f*) (+0.0025)	0.3235 (*a*, *b*, *f*) (-0.0065)	0.3280 (*a*, *b*, *e*, *f*) (-0.0020)
d	0.3404 (*b*) (+0.0104)	0.3354 (*e*, *f*) (+0.0054)	0.3325 (*a*, *b*, *e*) (+0.0025)	0.3349 (*a*, *b*, *e*, *f*) (+0.0049)
e	0.3366 (*b*) (+0.0066)	0.3351 (*c*, *d*) (+0.0051)	0.3335 (*a*, *c*, *d*) (+0.0035)	0.3270 (*a*, *b*, *c*, *d*) (-0.0016)
f	0.3371 (*b*) (+0.0071)	0.3222 (a, c) (-0.0078)	0.3367 (*a*, *b*, *d*) (+0.0067)	0.3315 (*a*, *b*, *c*, *d*) (+0.0015)
Mean	0.3340	0.3305	0.3315	0.3314
Std	0.0067	0.0045	0.0042	0.0030

where Std is standard deviation.

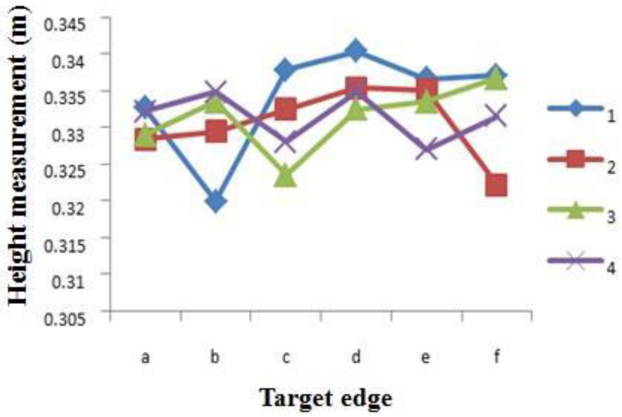

Figure-8. More measurement error is observed when using only 1 reference (blue) with respect to multiple references. The red straight line show the actual height of the boxes 0.33m.

Observation: From Figure-8 and Table-3, the measurement result become more accurate, closer to the actual height of the object, with the increasing number of reference heights used. Four reference heights produced a result with mean 0.3262±0.0162m (purple line, least flacutation) and 0.3218±0.0211m (blue line, bigger flacuating around the actual height of the measurement object) is produced when only one reference height is used.

CONCLUSIONS

The feasibility of performing horizontal and vertical measurement with single view geometry for road surveying is studied in this paper. Experiments were conducted by placing the calibration objects around 10 meters in front of the camera mounted at the rooftop of the survey vehicle. The reported accuracy of the horizontal measurement is 1.206±0.012m (0.5% offset, 1% standard deviation). For the vertical measurement, the location of the reference object was found influencing the accuracy of the measurement and the result of the measurement can be improved with the use of multiple reference objects.

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