10.2478/v10048-012-0013-x

Model-based Estimation for Pose, Velocity of Projectile from Stereo Linear Array Image

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The pose (position and attitude) and velocity of in-flight projectiles have major influence on the performance and accuracy. A cost-effective method for measuring the gun-boosted projectiles is proposed. The method adopts only one linear array image collected by the stereo vision system combining a digital line-scan camera and a mirror near the muzzle. From the projectile's stereo image, the motion parameters (pose and velocity) are acquired by using a model-based optimization algorithm. The algorithm achieves optimal estimation of the parameters by matching the stereo projection of the projectile and that of the same size 3D model. The speed and the AOA (angle of attack) could also be determined subsequently. Experiments are made to test the proposed method.

Keywords: Pose, velocity, projectile, speed, angle of attack, measurement, linear array image

1. INTRODUCTION

IT IS NECESSARY to capture the motion parameters, such as pose (including position and attitude), velocity (including speed and moving direction), and angle of attack (AOA, the angle of the attitude and the moving direction), of fast moving projectiles, bullets and missiles in weapon tests [1]. These parameters have major influence on the weapon performance and accuracy. Until recently, many optoelectronic-based [2-3], image-based methods [4-12], etc., have been employed to perform this task. Because of the relatively high quality resolution images that the advanced vision systems could provide, and maturity of the image processing algorithms, image-based methods have many benefits against alternative methods. These cameras are mainly divided into two kinds: area-scan camera [6-10] and line-scan camera [5,11,12]. The former always need multiple synchro-working cameras so that heavy data transmission and processing would be possible. Additionally, when the target is a fast moving one, it could have moved out of the frame before its scanning was completed. The latter mainly refers to streak cameras in real measurement [13,14]. The streak camera in synchro-ballistic mode has the ability to provide a large image with a clear background and a sharp deformed contour of a high speed target. Therefore, it is a popular tool in measuring the fast moving projectile in weapon test range. With the evolution of the digital sensor, it is a trend to develop a new means for recording and recovering the motion of this kind of fast moving target.

Digital line-scan camera uses one single linear array sensor to capture a two-dimensional image. The second dimension results from the relative motion between the object and the camera. A continuous or finite length image is captured line-by-line. Currently, this kind of camera is mainly used for automatic inspection [15,16], which could be considered as the digital version of the streak for non-contact measurement camera in streak photography. It also provides clear deformed projection of a moving target on one linear array image. Moreover, the images of fast moving objects come sharp and crisp with no need for expensive and cumbersome strobe lighting and shuttering. The image is composed of plenty of lines which are sensed at different time instants, it therefore contains both spatial and temporal information of the target's movement, making it particularly possible to estimate high-speed motion [17].

An original method is presented in this paper, which attempts to make use of a digital line-scan camera and maintain accuracy in position, attitude and velocity estimation for a fast moving projectile. In section 2, a stereo vision system combining a digital line-scan camera and a mirror near the muzzle is designed. From the projectile's stereo image obtained, an initial guess of the velocity and the pose (position and attitude) is proposed. Then the initial guess is further refined by an optimization algorithm based on the matching measure between the gradient information of the target's contour and that of its 3D model's. The speed and the AOA could also be obtained subsequently. Finally, experiments are presented and analyzed in section 3.

2. METHODS

A. Projection Model of the Vision System

a. Coordinate Definition

Three coordinates are established (Fig.1): image space coordinate $o-xyz$, with its origin o at the perspective center point of the camera, x and y axis vertical and parallel to the linear array sensor, respectively; 2D image plane coordinate $o'-x'y'$, with its origin o' at the principal point, x' and y' axis are parallel to x and y axis, respectively; target(projectile) coordinate $O-XYZ$, with its origin at the gravity center, X axis to the direction of the target.

b. Stereo Vision System

In order to record the 3D details of the target's movement, a new measurement system based on a line-scan camera and a mirror has been designed. A mirror is placed under the target's trajectory near the muzzle, at a 45°angle to the incident primary optical axis. The viewing plane, yz plane of coordinate $o-xyz$, should be vertical with the plane of mirror (Fig.1).Therefore, the target, and its reflection in the mirror (hereinafter virtual target), are simultaneously cut by the viewing plane. With continuous scanning, the stereo images of the target are generated on a single linear array image. This image contains the moving information of the target from two vertical directions.

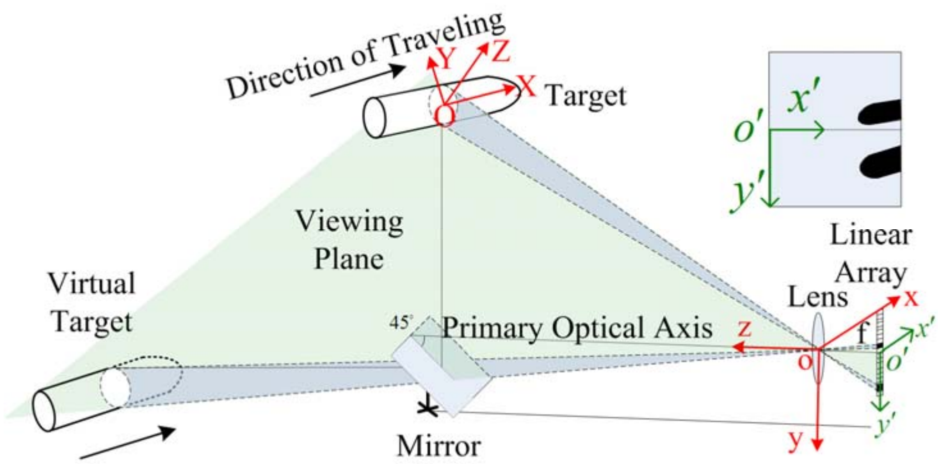


Fig.1. Stereo Vision System.

c. Dynamic Model

The target can be considered as an axisymmetric rigid object with a set of points. Let $\mathbf{P}=[X,Y,Z]^T$ be a 3D point lying on the rigid body, its coordinate in $o-xyz$ is given by $\mathbf{p}=[x,y,z]^T$. Let $\mathbf{T}$ be the translation vector and $\mathbf{R}$ be the rotation matrix, respectively, between the target coordinate and the image space coordinate. Note that if $\tilde{\mathbf{p}}=[\mathbf{p}^T,1]^T$, $\tilde{\mathbf{P}}=[\mathbf{P}^T,1]^T$, then the relationship between $\mathbf{p}$ and $\mathbf{P}$ is given by:

$$\tilde{\mathbf{p}}=\begin{bmatrix}\mathbf{R} & \mathbf{T}\\ \mathbf{0} & \mathbf{1}\end{bmatrix}\tilde{\mathbf{P}} \tag{1}$$

where $\mathbf{R}$ is related to the pitch α and yaw β, $\mathbf{T}$ is related to the velocity vector $\mathbf{V}=[V_x,V_y,V_z]^T$, time t, and the initial position $\mathbf{p_0}=[x_0,y_0,z_0]^T$, so $\mathbf{T}=t\mathbf{V}+\mathbf{p_0}$. The set of points lying on the target is considered as the dynamic model with respect to the motion parameters and t, which is given by $\Phi(\mathbf{V},\alpha,\beta,\mathbf{p_0};t)$.

d. Projection of the Dynamic Model

Let $m=[x',y']^T$ be the corresponding point of $\mathbf{p}=[x,y,z]^T$ on the image plane. The value of x' indicates the scanning time. Since the line scan camera is working in one–dimension mode, only the space points on the viewing plane ($x=0$) can be projected on the image plane. The projection model of the line-scan camera is well described in [17-19]: the relationship between the 3D point $\tilde{\mathbf{P}}=[\tilde{X},\tilde{Y},\tilde{Z}]^T$ in world coordinate and its corresponding point $m=[x',y']^T$ on the image plane is given by:

$$\begin{cases} y'=\dfrac{n_1\tilde{Y}+n_2\tilde{Z}+n_3}{n_4\tilde{Y}+n_5\tilde{Z}+1} \\ \text{subject to}\quad \tilde{X}=p\tilde{Y}+q\tilde{Z}+r \end{cases} \tag{2}$$

where $n_1,n_2,n_3,n_4,n_5,p,q,r$ are the parameters of the camera.

If the image space coordinate is taken as the measurement coordinate, the motion position, velocity and attitude studied in this article are all defined in the measurement coordinate, the relationship between m and $\mathbf{p}$ could be simply given by:

$$y'=-\frac{y}{z}f \tag{3}$$

where f is the focus length of the camera.

Since the period the dynamic model is moving across the viewing plane is very short, $\mathbf{V},\alpha,\beta$ seem to be unchanged. When the dynamic model begins to be cut by the viewing plane, one-dimensional projection is captured line by line to integrate a two-dimensional linear image, with a deforming contour of object projection.

B. Estimation for the Pose and the Velocity

The estimation procedure for the pose and velocity is divided into two steps: initial guess is firstly determined from the space and projection relationships among the special points in the stereo images. Then the initial guess is further refined by using an optimization algorithm taking the whole information of the stereo images into account.

a. Initial Guess

In Fig.2(a), A,A' are the spatial positions of the tips of the target and virtual target's centerlines when they reach the linear array, respectively, and B, B' are the spatial positions of the tails when they reach the linear array, respectively. The time t of the target flying across the linear array is from 0 to T. C, D, C', D' are the bottom's lower and upper fringes. Fig.2(b) shows the stereo images of the target obtained using the stereo vision system. a, a' are the projections of the tips. c, d, c', d' are the projections of the bottom fringe, respectively. b, b', middle of cd, $c'd'$, are the projections of the tails. a and a', b and b' are two pairs of homologous image points. According to the equation (3) and the orthogonal relationship, the space positions of the tip $A(0, y_1, z_1)$ and the tail $B(0, y_2, z_2)$ can be obtained from intersections of the homologous points.

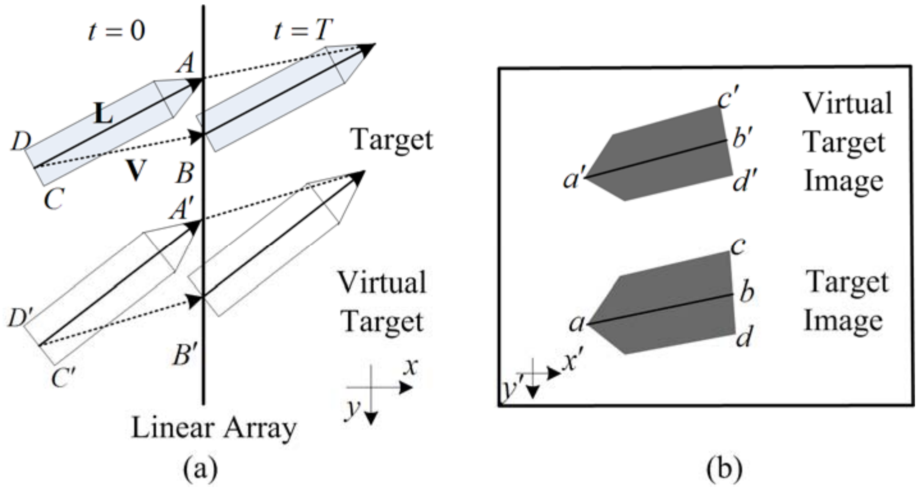


Fig.2. (a) The displacement of the target and its virtual counterpart in space (seen in the direction of the axis z); (b) stereo images of the target.

The motion parameters, velocity, attitude and position, are described by $V_x, V_y, V_z, \alpha, \beta, x_0, y_0, z_0$. Let the midline vector be $\mathbf{L}(L_x, L_y, L_z)$, then the target length

$$L = \sqrt{L_x^{\ 2} + L_y^{\ 2} + L_z^{\ 2}},$$

$\alpha = \arctan(L_y / L_x)$, $\beta = \arcsin(L_z / L)$. The time the target is flying across the viewing plane, T, can be computed from the length of the target's projection covers on the x' axis, so:

$$L_x = V_x T \tag{4}$$

$$y_2 = y_1 - L_y + V_y T \tag{5}$$

$$z_2 = z_1 - L_z + V_z T \tag{6}$$

Suppose the time across the array from C to D is Δt, from C' to D' is $\Delta t'$, the target's diameter R is known, the relationships could be obtained:

$$R\frac{L_y}{L} = V_x \Delta t \tag{7}$$

$$-R\frac{L_z}{L} = V_x \Delta t' \tag{8}$$

$V_x, V_y, V_z, L_x, L_y, L_z$ are the solution of the linear equations (4)~(8). x_0, y_0, z_0, the gravity of the target, can be computed by y_1, z_1, y_2, z_2. α, β can be determined from L_x, L_y, L_z.

Thus, an initial guess of the motion parameters of the target is obtained from a series of special points on the stereo images of the target.

b. Optimization Algorithm

The initial guess of the motion parameters of the target is only a rough estimation, and its accuracy and robustness depend on the special points. Commonly, an optimization algorithm is necessary in this case. Our scheme is, firstly, an image simulating program developed in Visual C++ 6.0 software to generate a simulated image based on the projection model presented.

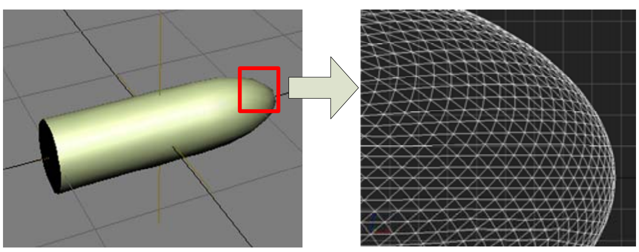


Fig.3. the 3D digital model of the projectile with its triangular mesh surface.

The key procedure of the optimization algorithm is to generate the simulated image of the target's 3D digital model, which is established in 3D MAX software. The digital model generated in 3D MAX is a 3D body whose surface consists of triangular mesh (as shown in Fig.3). The coordinate values of the vertices of the triangular mesh could be imported from the 3D data of the model. These coordinate values of the vertices could be transformed into the spatial points of the dynamic model. Therefore, the simulated image could be obtained via the simulating program with respect to preset motion parameters. The simulated image and the real image are compared. When the preset parameters can produce a simulated image that is well-matched with the real one, the parameters of the dynamic model can be considered as a reasonable estimation of the real motion parameters.

Therefore, the estimation of motion is transformed into a problem of image-matching. Our task is to adjust the motion parameters of the dynamic model to reduce the difference between the simulated image and the real one. An optimization algorithm based on the gradient information of the real and simulated image is used to achieve the task. The procedure is shown in Fig.4:

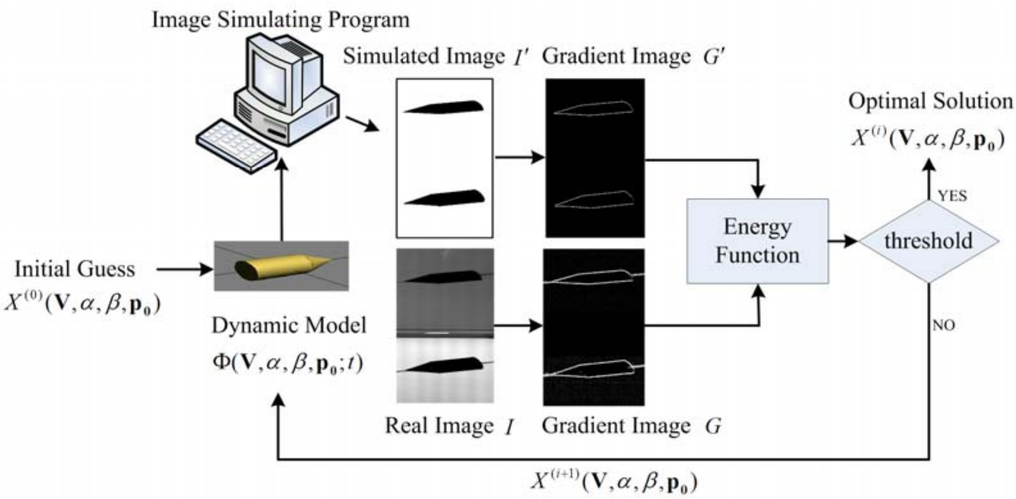


Fig.4. The flow of motion parameter estimation.

Let $(x_i, y_j), i = 1\cdots N, j = 1\cdots M$ be the $N\times M$ pixels of real image I. Since the linear array image is composed of scanning lines, the gradient magnitude is computed only on one-dimension. Let the gradient image be G, and then

$$G(x_i, y_j) = | I(x_i, y_{j+1}) - I(x_i, y_j) |, i = 1\cdots N, j = 1\cdots M-1 \tag{9}$$

Let $(x'_i, y'_j), i = 1\cdots N, j = 1\cdots M$ be the $N\times M$ pixels of simulated image I' related to the dynamic model $\Phi(\mathbf{V},\alpha,\beta,\mathbf{p_0};t)$. Let the gradient image be G', and then:

$$G'(x'_i, y'_j) = | I(x'_i, y'_{j+1}) - I(x'_i, y'_j) |, i = 1\cdots N, j = 1\cdots M-1 \tag{10}$$

We want to find $X(\mathbf{V},\alpha,\beta,\mathbf{p_0})$ that minimize the following energy function:

$$\varepsilon = \sum_{i=1}^{N}\sum_{j=1}^{M-1}[G'(x'_i, y'_j) - G(x_i, y_j)]^2 \tag{11}$$

Thus, the optimization model is given by:

$$\min\varepsilon = \min\{\sum_{i=1}^{N}\sum_{j=1}^{M-1}[G'(x'_i, y'_j) - G(x_i, y_j)]^2\} = \min(\| g' - g \|_2) \tag{12}$$

Where g', g are the vectors of the gradient image of the simulated and real image, $g', g \in R_+^{N\times(M-1)}$.

The optimization model can be solved using an improved nonlinear Powell optimization algorithm. It is obvious that an initial guess $X^{(0)}(\mathbf{V},\alpha,\beta,\mathbf{p_0})$ would be helpful to converge towards an optimal solution of the motion parameters $X^{(i)}(\mathbf{V},\alpha,\beta,\mathbf{p_0})$. If the motion parameters are known, the speed v and angle of attack φ could be obtained by:

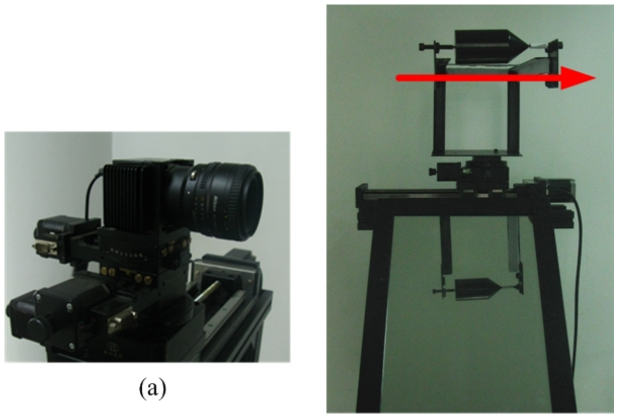
$$v = \sqrt{V_x^2 + V_y^2 + V_z^2} \tag{13}$$

$$\varphi = \arccos(\frac{L_x V_x + L_y V_y + L_z V_z}{Lv}) \tag{14}$$

3. EXPERIMENT

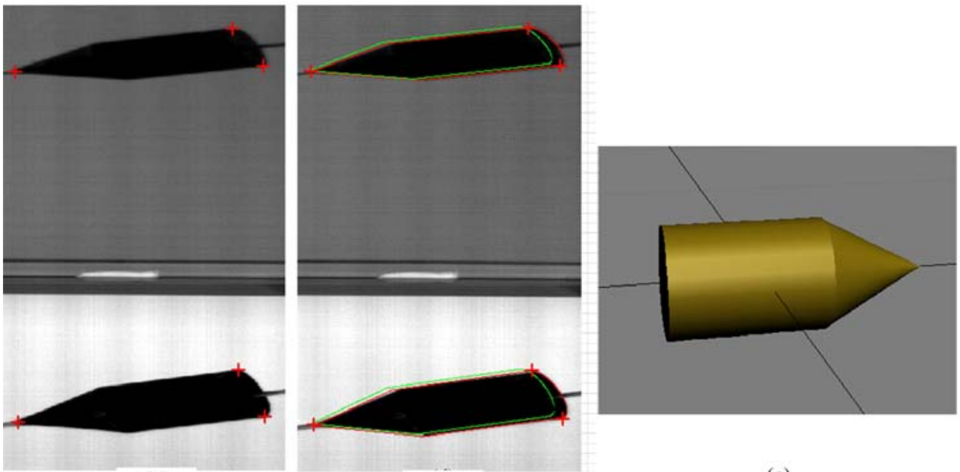
Experiments have been conducted in laboratory to test the proposed method. A reduced scale projectile-like model target has been used. The stereo vision system (BASLER spL2048-140km line-scan camera and mirror) is shown in Fig.5. The exact spatial relation of the vision system and the parameters of the camera are determined by a camera calibration. Pan-tilt control and mechanism-driven linear guide rail ensure the precise attitude, moving speed of the model target. The attitude and speed parameters can be preset. These preset values can be regarded as ground truth which is hardly available in real weapon tests.

The stereo linear array image of the moving reduced scale target is captured line by line at a scanning rate of 50line/second (when the target is a fast moving one, the camera scanning rate would reach 140k line/second). Special points are picked (Fig.6(a)) to give an initial guess of the motion parameters, and then, the image-matching optimization algorithm based on the 3D model of the reduced scale (Fig.6(c)) model is used to converge to an optimal estimation. A highlight of the method is that the motion parameter estimation is treated as an image-matching problem. To illustrate the effectiveness of the method, the stereo projections of the target related to the initial (green contour) and the optimal estimation (red contour) of the motion parameters are simulated in Fig.6(b). It shows that the optimal estimation result achieves a distinctly better match with the real projection of the target than the initial guess, which means the method has a reasonably good accuracy in the motion estimation.



(a) (b)

Fig.5. (a) digital line-scan camera(BASLER spL2048-140km); (b) moving reduced scale model target and its reflection in the mirror.



(a) (b) (c)

Fig.6. (a) stereo image and special points; (b) the stereo projections related to the initial and the optimal estimation results; (c) 3D model of reduced scale model.

Tab.1. The comparison of the preset values and the measured values.

No.	Preset values			Measured values			Relative errors		
	Yaw(deg.)	Pitch(deg.)	Speed*(m/s)	Yaw(deg.)	Pitch(deg.)	Speed(m/s)	Yaw(%)	Pitch(%)	Speed(%)
1	2	3	30	1.958	2.917	30.125	2.10	2.77	0.42
2	3	0	50	3.047	0.120	49.872	1.57	---	0.26
3	-5	5	80	-4.913	5.114	80.114	1.74	2.28	0.14
4	10	-5	100	9.977	-4.96	100.152	0.23	0.80	0.15
5	0	10	120	-0.021	9.833	119.569	---	1.17	0.36
6	-10	5	150	-9.916	5.078	150.371	0.84	1.56	0.25

*different preset speed could be given by different sampling rate of the collected image

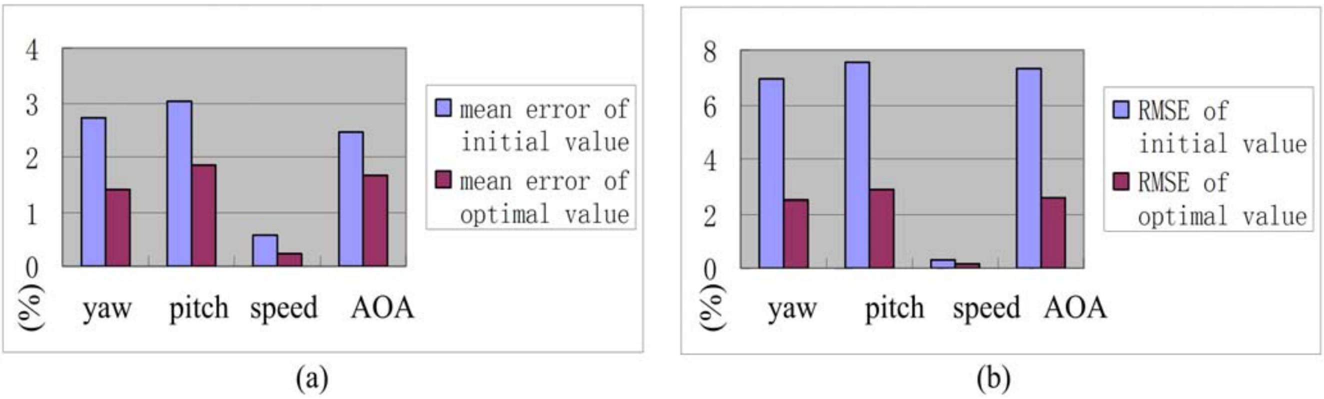


Fig.7. Comparison between the initial and optimal values: (a) the mean values of the relative errors; (b) RMSE of the relative errors.

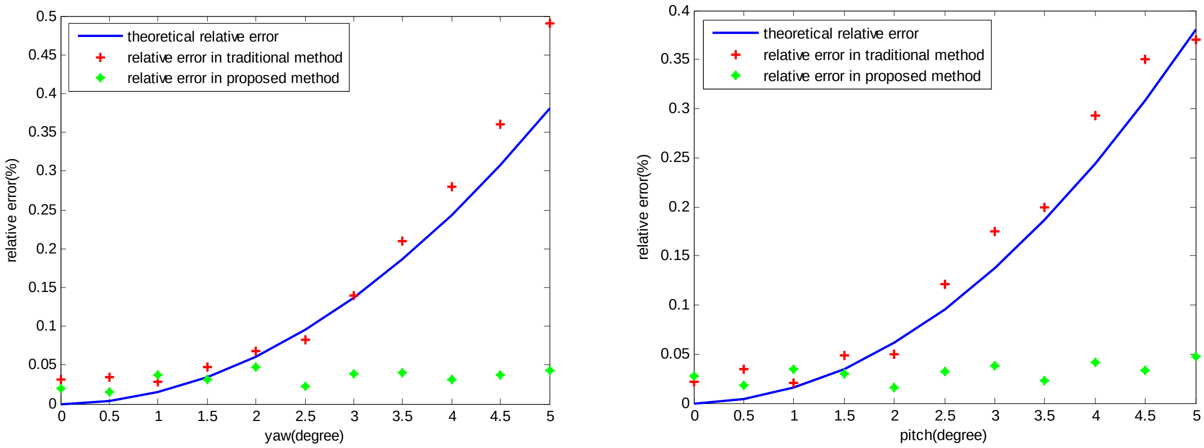


Fig.8. Relative errors of the speed estimation with yaw and pitch changing.

Multiple tests with respect to different preset motion parameters have been made. Tab.1 presents a list of six groups of data collected in these tests. Taking the preset parameters as ground truth values, the mean values and RMSE of the relative errors are computed and illustrated in Fig.7. It shows that, comparing with the initial values which are only determined by several special points, the optimization algorithm obviously improves the accuracy and the robustness of the estimation.

It is noted that the method is not a full automatic one. A human-computer interface has been developed so that a manual operation could be made for the location of the special points. In spite of this, the method really improves the efficiency of the parameter estimation. In our tests, the time that each image (2048 pixels *1024 pixels) is simulated is less than 0.01 seconds, and the mean time of the optimization algorithm costs is 6.2 seconds.

The proposed method would improve the traditional streak technology on the scope and accuracy of measurement. The algorithms presented in [11] and [12] are still used in streak photography of a high speed projectile. Its accuracy requires the direction of the moving target to keep completely perpendicular to the streak (linear array sensor). Our method circles the problem out by considering the velocity, attitude and position as 3D elements and solves them separately, so our method leads to a more general and accurate estimation of the pose and the velocity. The relative errors of the speed estimation in the proposed method with the yaw, and the pitch changing are compared with the theoretical and test relative errors in a traditional method (Fig.8). It shows that the proposed method still maintains good accuracy when the target's attitude is changing.

To test and verify the performance of the method, a series of experiments have been made using the stereo linear image collected in Test Range. The method shows good robustness and accuracy in the tests of 82mm projectile whose speed near the muzzle could reach 320m/s.

4. Conclusion

A cost-effective non-contact stereo vision system is designed and an optimization algorithm for estimating the high-speed projectile is presented in this paper. The method improves the traditional streak photographic technique by making digital line-scan camera an alternative to the traditional streak camera. It also presents a model-based optimization algorithm on the matching measure of the gradient information between the simulated and the real image. The optimization algorithm improved the accuracy of the initial guess by taking the whole contour information into account rather than several special points.

The method reduces the amount of data and the computational cost, because only one line-scan camera is used and only one image is processed. It helps to make the line-scan camera a promising tool in estimating 3D motion, especially for high-speed targets. Additionally, although the camera calibration is not given in detail in this paper, it is indispensable in measurement work [18-20].

Since the precision of the 3D model is significant to ensure the effectiveness of the optimization matching, the proposed method is limited to use in measuring a known target, such as a projectile or bullet in a weapon test range.

ACKNOWLEDGMENT

The work was supported by the National Natural Science Foundation of China under Grant No. 60872153. The authors are also grateful for the help of the colleagues in ATR Key Laboratory and Ms. Lilin.

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Received November 8, 2011.
Accepted May 25, 2012.