Application of Kalman Filter in Track Prediction of Shuttlecock

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Application of Kalman Filter in Track Prediction of Shuttlecock

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Abstract - This paper deals with the application of Kalman filter for optimizing and filtering the position signal of shuttlecock obtained by the vision servo system of 'Shuttlecock Robot' [1]. Non-uniform mass distribution and air resistance effect can make much noise not only in vision recognition but also in kinematic model analysis of shuttlecock. The Kalman filter algorithm is used to filter the shuttlecock position signal by taking the error of measurement and the error of shuttlecock motion model into account. Besides, by considering the requirement of fast moving control, we reduce dimensions of state vector by decomposition of shuttlecock motion to shorten the executive cycle. The simulation results show its affectivity on improving the accuracy of track prediction. It can also accomplish track prediction fast and accurately when applied on 'Shuttlecock Robot'.
Keywords: least squares, Kalman filter, air resistance, Shuttlecock Robot

I. INTRODUCTION

In modern field of robot, sport robots have been reported a lot and a great many researches have been done in this field, but there is little report on the research of shuttlecock robots. 'Shuttle Robot' is a new kind of sport robot. Shuttlecock Robot is a new research area of vision servo system application and system control strategy research. Generally, the system of Shuttlecock Robot is composed of three core parts, vision subsystem, servo subsystem and machinery subsystem [1], which is shown in Fig.1 [2].Vision subsystem is used to obtain the position signal of shuttlecock, servo subsystem and machinery subsystem are the executive devices with three degree freedom. When the robot is in operation, the two motors are controlled to position the robot leg to the predicted fall-point of shuttlecock, and the third motor will hit the shuttlecock at the required time, so the accuracy of track prediction is so important that it will decide the executing effect of executive device.

However, track prediction of irregular-shaped object such as shuttlecock based on information obtained by vision system also has several problems which are difficult to be solved by most of current methods:

Firstly, the shape of shuttlecock is irregular, and its centroid is too difficult to be recognized well by vision system when flying in the air randomly. So it is impossible to obtain the position signal of shuttlecock by vision system

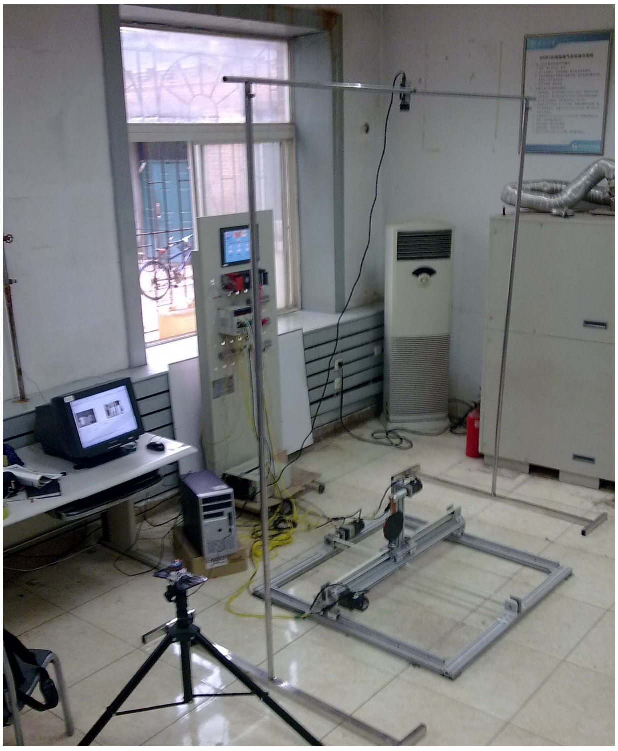


Fig.1 Real system of shuttlecock robot

without any errors and noise even by the vision recognition algorithm in [11] and [14] or most of other image processing algorithms proposed until now.

Secondly, the kinematic model of shuttlecock is a special kind of projection motion model. A model of projection motion is proposed in [13]. However, as shuttlecock is a kind of irregular-shaped object which is affected by air resistance intensely when rotating and flying in the air, so the motion of shuttlecock is too complex to be described without any error.

Thirdly, because the accuracy of track prediction is associated with the sampling frequency of vision system, it is important to shorten the executive cycle [7]. However, having too many dimensions of the state vector is a universal problem in many Kalman filters such as the one proposed in [12], which is disadvantage to shorten the executive time.

Considering the above-mentioned problems, this paper at first analyzes the kinematic model of shuttlecock, and then the algorithm of track prediction based on the model is proposed. In order to optimize and filter the position signal of shuttlecock before track fitting, Kalman filter is added. By the time the suitable values of parameters R (measurement error matrix) and Q (model error matrix) is set, the vision recognition errors and model errors are taken into account. However, because the motion of shuttlecock is in three-dimensional space, all variables of position, velocity, and acceleration in three 'x, y and z' dimensional space are needed to describe the motion and to calculate in Kalman filter, but if at first the kinematic model is decomposed into 'x, y and z' three axes, then Kalman filter can be applied in three axes separately. As every filter only has a three-dimension process state vector, the total time spent on matrix operations in Kalman filter algorithm can be much less [6].

II. GENERALLY INTRODUCTION OF ALGORITHM OF TRACK PREDICTION AND FALL POINT FORECASTING

In order to get accurate and adequate information of shuttlecock motion, the kinematic track equation of shuttlecock is obtained by track fitting through series of position information of shuttlecock, then several important information such as the position of fall point, and fall time of shuttlecock can be solved by the equations. As an improvement, as shown in Fig.2,the position information of shuttlecock is optimized by the application of Kalman filter before the track of shuttlecock motion is fitted so that not only the position information of shuttlecock is obtained more accurately, but also the velocity and acceleration information can be acquired, which contribute to more effective control of Shuttlecock Robot.

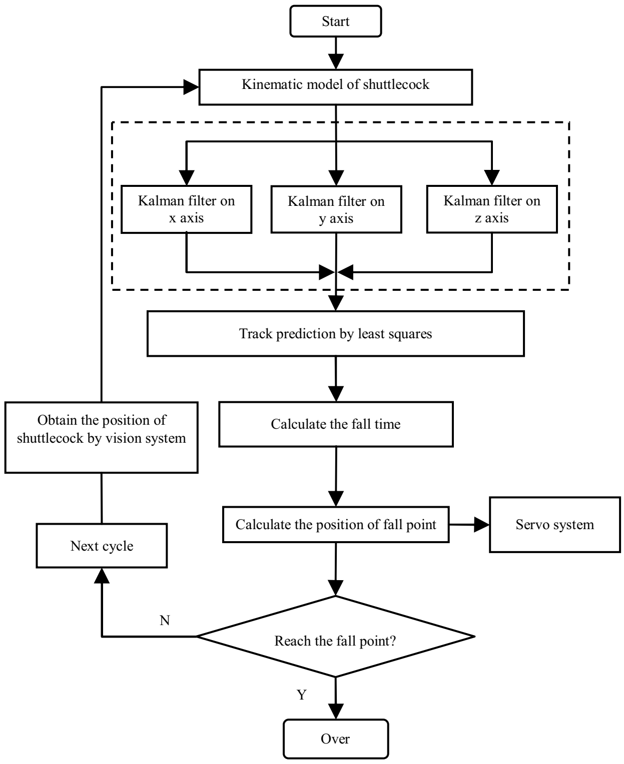


Fig.2 Flowchart diagram of track prediction and fall point forecasting

III. ANALYSIS OF KINEMATIC MODEL OF SHUTTLECOCK MOTION

1) Analysis on Kinematics

By analyzing the motion of shuttlecock on kinematics, we know it is a kind of motion with a variable acceleration:

$$\begin{cases} s(t) = \int v(t)dt + s_0 \\ v(t) = \int a(t)dt + v_0 \end{cases} \tag{1}$$

Where $s(t)$ is the position, $v(t)$ is the velocity and $a(t)$ is the acceleration of shuttlecock while s_0 is the initial position and v_0 is the initial velocity.

2) Analysis of Air Resistance Model

a) Description of the Air Resistance Based on General Air Resistance Model

$$f = -k_1 v - k_2 v^2 \tag{2}$$

Where k_1 and k_2 are inherent parameters which are related to the volume and shape in the absence of variation of atmospheric density.

Considering (1) and (2), we regard the state variables of Kalman filter as a vector which has more than 9 dimensions.

Besides, there are coupling relationships of x, y and z because of quadratic term in (2). Because of several operations of 9×9 matrix, especially inverse operations of matrix, the executable cycle is too long to satisfy the request of high speed [10]. Therefore the practical method is described as below.

b) Simplification of Air Resistance Model Based on Theoretical Analysis and Measurement

The air resistance model of shuttlecock is analyzed again. It is a fact that the range of the height of shuttlecock motion is within 1 meter, so the maximum speed of the shuttlecock must be within 5m/s which is much smaller than the velocity of low-speed bullet that we can use the air resistance model of low-speed objects. Besides, through the measurement of the parameters of air resistance model of shuttlecock we know that $k_2 << k_1$ .All in all, the air resistance model of shuttlecock is simplified as below

$$f = -kv \tag{3}$$

Where k is the parameter of air resistance of shuttlecock. Considering the gravity, we get

$$\vec{a} = \frac{\vec{f} + \vec{G}}{m} \tag{4}$$

3) Kinematic Equations of Shuttlecock Motion

The acceleration of shuttlecock motion is decomposed into x, y and z three dimensions based on (3) and Fig.3.

$$\begin{cases} a_x m = f_x = -f \cdot \cos\theta \cdot \sin\varphi = -kv \cdot \cos\theta \cdot \sin\varphi = -kv_x \\ a_y m = f_y = -f \cdot \sin\theta \cdot \sin\varphi = -kv \cdot \sin\theta \cdot \sin\varphi = -kv_y \\ a_z m = f_z - mg = -f\cos\varphi - mg = -kv \cdot \cos\varphi - mg = -kv_z - mg \end{cases} \tag{5}$$

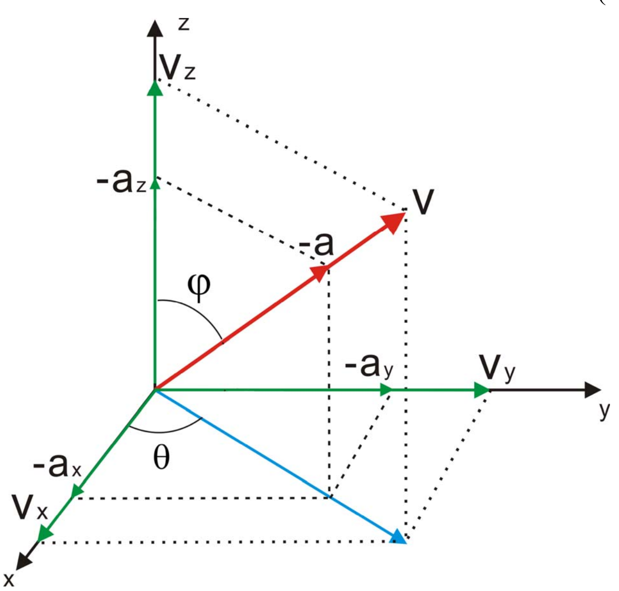


Fig.3 The decomposition of velocity and acceleration of shuttlecock motion

From (5) and (3), we have:

$$\begin{cases} x(t) = -\frac{v_{x0}m}{k}e^{-\frac{k}{m}t} + \frac{mv_{x0}}{k} + x_0 \\ y(t) = -\frac{v_{y0}m}{k}e^{-\frac{k}{m}t} + \frac{mv_{y0}}{k} + y_0 \\ z(t) = -(\frac{m^2 g}{k^2} + \frac{v_0 m}{k})e^{-\frac{k}{m}t} - \frac{mgt}{k} + \frac{m^2 g + mv_0 k}{k^2} + x_0 \end{cases} \tag{6}$$

So the motion of shuttlecock is decomposed into x, y and z three dimensions.

IV. TRACK FITTING OF SHUTTLECOCK MOTION WITH THE KINEMATIC MODEL AND POSITION OF SHUTTLECOCK

The equation of x-axis is used for example:

Firstly $x(t) = -\frac{v_{x0}m}{k}e^{-\frac{k}{m}t} + \frac{mv_{x0}}{k} + x_0$ is transformed to:

$$y = a_0 x + a_1 \tag{7}$$

Where x is equal to $\frac{m(1-e^{-\frac{k}{m}t})}{k}$.

Then the track is fitted by least squares [8], and (8) is obtained as below:

$$\begin{cases} \sum_{i=0}^{k}(y_i - a_0 x_i - a_1) \cdot x_i = 0 \\ \sum_{i=0}^{k}(y_i - a_0 x_i - a_1) = 0 \end{cases} \tag{8}$$

By solving the equations, we can get the values of a_0 and a_1.

Similarly, the track equations of y-axis and z-axis are solved in the same way and then the track equations of shuttlecock motion are obtained.

V. OPTIMIZATION OF THE POSITION INFORMATION OF SHUTTLECOCK MOTION BY KALMAN FILTER

1) Discrete State Transition Equations of Shuttlecock Motion

In reference to equations of shuttlecock motion and time discretization of vision system, the discrete form of equations of shuttlecock motion is obtained. As the sampling cycle is very small (almost 1/30 second) and the value of velocity of shuttlecock can not change sharply because of the initial effect, the velocity and acceleration (see (5)) of shuttlecock motion are considered as constant in the period of a cycle. With (5) and equations of uniformly accelerated motion, we have the state transition equations of shuttlecock motion:

$$\begin{cases} x(i) = x(i-1) + \dot{x}(i-1) + \dfrac{\ddot{x}T^2}{2}(i-1) \\ \dot{x}(i) = \dot{x}(i-1) + \ddot{x}(i-1)\cdot T \\ \ddot{x}(i) = -\dfrac{k}{m}\dot{x}(i) = -\dfrac{k}{m}[\dot{x}(i-1) + \ddot{x}(i-1)\cdot T] \end{cases} \tag{9}$$

2) Descriptions of Kalman Filter [3] [5] [9]

a) Computation of state transition

The process from one state to another is governed by (10).

$$X(i\,|\,i-1) = A\cdot X(i-1\,|\,i-1) + \text{X\_Y\_OR\_Z}\cdot B\cdot U(i) \tag{10}$$

Where $X(i) = \begin{bmatrix} x(i) \\ \dot{x}(i) \\ \ddot{x}(i) \end{bmatrix}$ is state matrix of the system.

$U(i) = [-g]$ is the control matrix and g represents acceleration of gravity. X_Y_OR_Z is a Boolean data which is '0' while the axis is 'x' or 'y' and '1' while axis is 'z'. The 3×3 matrix A relates the state at the previous time step $X(i-1\,|\,i-1)$ to the state at the current step $X(i\,|\,i-1)$ under the circumstance of not considering control matrix [4]. According to (9), we have $A = \begin{bmatrix} 1 & T & \dfrac{T^2}{2} \\ 0 & 1 & T \\ 0 & -\dfrac{k}{m} & -\dfrac{kT}{m} \end{bmatrix}$.

b) Computation of error covariance

$$P(i\,|\,i-1) = A\cdot P(i-1\,|\,i-1)\cdot A' + Q \tag{11}$$

Where $P(k)$ is state vector error covariance matrix and Q is process noise covariance.

c) Updating of the estimate with measurement $Z(k)$

$$X(i\,|\,i) = X(i\,|\,i-1) + Kg(i)[Z(i) - H\cdot X(i\,|\,i-1)] \tag{12}$$

$$Kg(i) = \frac{P(i\,|\,i-1)\cdot H'}{H\cdot P(i\,|\,i-1)\cdot H' + R} \tag{13}$$

Where $Kg(i)$ is Kalman gain and $Z(i)$ is the measurement vectors. $H = [1 \quad 0 \quad 0]$ is a 1×3 matrix giving the ideal(noise-free) connection between the measurement and state vector while H' is transpose of it. R is measurement error covariance.

d) Computation of error covariance for updated estimate.

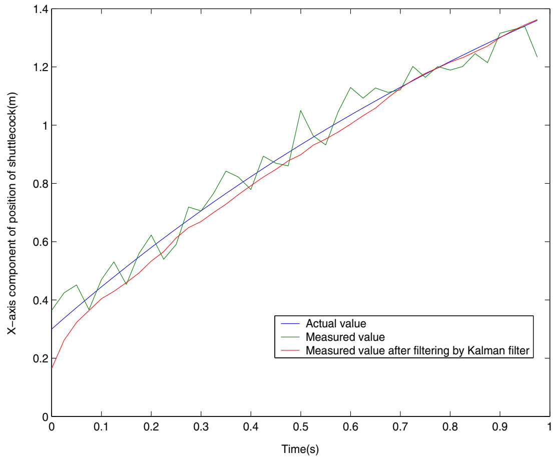
$$P(i\,|\,i) = (I - Kg(i)\cdot H)\cdot P(i\,|\,i-1) \tag{14}$$

Where I is a 3×3 unit matrix.

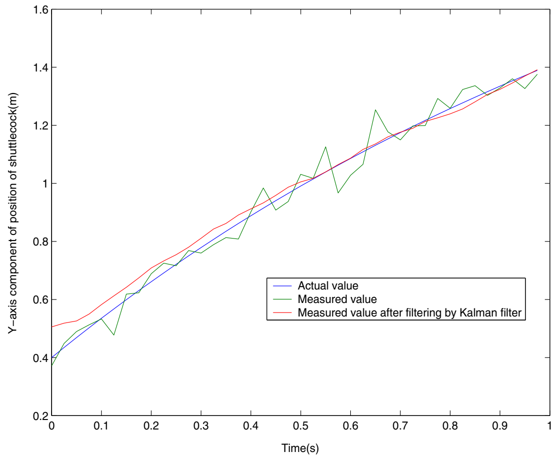
VI. SIMULATION RESULTS

In order to evaluate results of Applying Kalman filter in track prediction of shuttlecock motion, several experiments are done on Matlab. Firstly, the measured values obtained by vision system are simulated by inputting white noise whose signal-to-noise ratio is 25 into actual values. Besides, we set the process noise covariance Q as 0.04 while measurement error covariance R as 0.04.

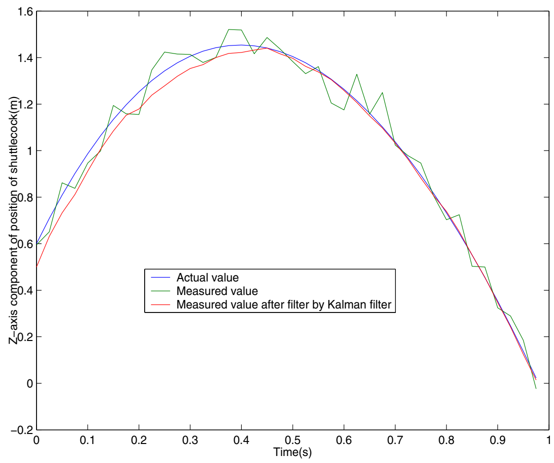
1) The measured values, the filtered measured values by Kalman filter and the actual values of position of shuttlecock are compared on x-axis, y-axis and z-axis, as shown in Fig.4 (a), Fig.4 (b) and Fig.4(c).



(a)



(b)



(c)

Fig.4 (a) Comparison of the measured values, the filtered measured values by Kalman filter and the actual values of shuttlecock position on x-axis, (b) Comparison of the measured values, the filtered measured values by Kalman filter and the actual values of shuttlecock position on y-axis, (c) Comparison of the measured values, the filtered measured values by Kalman filter and the actual values of shuttlecock position on z-axis.

Results analysis:

Through Fig.4 (a), Fig.4 (b) and Fig.4 (c) some conclusions are reached. Firstly, the errors of measurement are minimized by the use of Kalman filter. Secondly, velocity and acceleration of shuttlecock motion are obtained which are useful to servo system. Thirdly, the curves of the filtered measured values by Kalman filter converge to the curves of actual values.

2) Comparison of the convergence of fall-point position prediction between using Kalman filter and not using Kalman filter

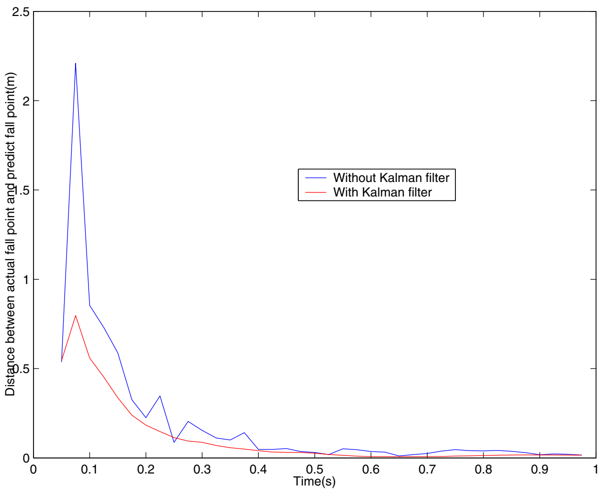


Fig.5 Comparison of the convergence of fall-point position prediction

Results analysis:

As shown in Fig.5, after Kalman filter is added, the fluctuation of errors of track prediction is smaller, the convergence of errors of track prediction is faster, and the steady state value of errors of track prediction is much smaller than before, which are very important for controlling shuttlecock robot quickly, steadily and accurately.

VII. SUMMARY AND CONCLUSIONS

This paper concerns about the accuracy of recognition and track prediction of irregular-shaped object by binocular vision system. In reference to the simulation results, some conclusions are acquired: By using Kalman filter, the noise of recognition is reduced, the velocity and acceleration of shuttlecock are obtained, the accuracy of track prediction is improved, and the fall-point of shuttlecock is predicted faster and more accurately. These improvements mentioned above are important for us to control Shuttlecock Robot well.

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