Method for Robot Capturing Object Thrown out in Natural Wind Environment

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Abstract. It is difficult for a robot to capture object which is thrown out in the environment with natural wind. Equation of state and measurement of the object in the environment with natural wind is studied. Using the measurement equation and the state equation when there is no natural wind, the average acceleration of the object caused by natural wind can be estimated. Moreover, the variance of the object acceleration caused by natural wind can be estimated using the statistical characteristics and probability distribution of natural wind. Then a method for robot capturing the object based on Kalman filter is proposed. Simulation results show that the trajectory of the object changes obviously when two groups of typical natural wind are used. The object trajectory can be tracked by the robot accurately after it deviates from the object trajectory for about eight sampling periods.

1. Introduction
With the expanding application of robots, the research of robot catching object which is thrown out (hereinafter referred to as the object) has attracted considerable attention and research of scholars at home and abroad [1,2]. The method of realizing the coordinated movement of the robot arm and the base under the control of the space robot arm in the condition of the free-floating of the base is proposed, which can realize the capture of the object with known trajectories [3]. Additionally, with the assumed modal method, the one-way recursive set method, and the established dynamic equations of the system by the Jourdain velocity variation principle [4], the object with known trajectories is captured. Furthermore, a capturing method of estimating the rotational motion by the depth image sensor is proposed for realizing the capturing of satellites in orbit in space [5]. The above researches on capturing the object are based on the premise that the thrown trajectory is known.

In the field of catching the object with unknown trajectories, table tennis is used as the object, visual equipment is used to collect the position of table tennis [6,7], a seven degree of freedom robotic arm is used to strike small balls with unknown trajectories [8]. With a method which is called system identification, the ping-pong trajectory is predicted and a ping-pong robot control system is formed by a six degree of freedom robot to achieve hits on unknown balls [9]. A scheme of capturing non-
cooperative targets is presented the target characteristics are measured and estimated and also achieve capture [10], the interference of non-cooperative targets is not considered in this system. To sum up, in recent years, researches on the object in which trajectory is unknown captured by robot and achieved some results, but the distribution of the catching system is small. Due to the speed of natural wind is unknown and inconstant [11,12], the trajectory of the object will be a complex unknown curve. However, the driving force of the aircraft and other vehicles is unknown, the above methods cannot be used to capture the object. Aiming the unknown driving force which acts on an air vehicle, a method which the carrier’s driving force can be calculated in real-time is deduced by Professor Zhou [13]. Then, the adaptive Kalman filter was proposed to tract carriers in real-time.

Since the position of the object can be measured and calculated by the visual system in real-time, the trajectory of the object is known without natural wind, the force which acted on the object caused by natural wind can also be estimated. Then a Kalman filter method which variance and control variables can be updated in real-time can be proposed, so the object can be caught by robot in the environment with natural wind.

2. Method of Robot Catching the Object

2.1. Construction of the Object State Equation and Measurement Equation

The trajectory of the object will be affected by natural wind. By studying the equation of measurement and state, the mean value of natural wind is estimated, the variance of the acceleration of the object is updated in the Kalman filter method.

As shown in figure 1, the force caused by natural wind can be decomposed into $F_x, F_y, F_z$. Meantime, the object is also affected by gravity, $F_x, F_y, F_z$ caused by natural wind are random and unknown. Therefore, to study the state equation and measurement equation of the system in natural wind environment, the average value of $F_x, F_y, F_z$ in a control period should be taken. Let the average value of $F_x, F_y, F_z$ in a control period be $\bar{a}_x, \bar{a}_y, \bar{a}_z$, position, and velocity in $x, y,$ and $z$ directions are used as state variables $X(k) = [P_x(k), V_x(k), P_y(k), V_y(k), P_z(k), V_z(k)]$. The state equation of the thrown motion in natural wind environment can be established in figure 1.
\[
\begin{bmatrix}
    P_i(k) \\
    V_i(k) \\
    P_i(k) \\
    V_i(k)
\end{bmatrix} = \phi \cdot 
\begin{bmatrix}
    P_i(k-1) \\
    V_i(k-1) \\
    P_i(k-1) \\
    V_i(k-1)
\end{bmatrix} + B_i \cdot G + B_2 \cdot A_w + \Gamma \cdot W(k)
\] (1)

Where \( \phi \) represents the state transition matrix.

\[
\phi =
\begin{bmatrix}
1 & T & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & T & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & T \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\quad , \quad B_i =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{2}T^2 & g & 0 & 0 & 0 & 0 \\
T & g & 0 & 0 & 0 & 0
\end{bmatrix}
\] (2)

Where \( G \) is the acceleration of gravity, only affects the thrown force in the z-axis direction, where \( B_i \) is the driving matrix of \( G \).

\[
B_2 =
\begin{bmatrix}
T^2/2 & 0 & 0 \\
T & 0 & 0 \\
0 & T^2/2 & 0 \\
0 & T & 0 \\
0 & 0 & T^2/2 \\
0 & 0 & T
\end{bmatrix}
\quad , \quad A_w =
\begin{bmatrix}
\frac{a_x}{a_x} \\
\frac{a_y}{a_y} \\
\frac{a_z}{a_z}
\end{bmatrix}
\] (3)

Where \( A_w \) is the mean natural wind acceleration in the x, y, and z directions, and \( B_2 \) is the driving matrix of \( A_w \).

\[
\Gamma =
\begin{bmatrix}
T^2/2 & 0 & 0 \\
T & 0 & 0 \\
0 & T^2/2 & 0 \\
0 & T & 0 \\
0 & 0 & T^2/2 \\
0 & 0 & T
\end{bmatrix}
\quad , \quad W(k) =
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z
\end{bmatrix}
\] (4)

In the equation of state, the gravity of the object \( B_i \) and \( G \) are known. Natural wind and its acceleration mean are unknown. Where \( W(k) \) is the system noise which is affected by the average value of gravity and natural wind acceleration of the object, and \( Q \) is the variance of \( W(k) \), and \( \Gamma \) is the driving array of system noise.

In the system of catching the object by robot, the visual acquisition system is used to observe the object-based coordinate system. The measurement equation is constructed as
The observed noise $V(k)$ in equation (5) is Gaussian white noise with variance $R$ and mean zero. Where $(P_x(k), P_y(k), P_z(k))$ is the position of the object at time $k$.

2.2. Deduction of the Mean Value of Natural Wind Acceleration

Mean acceleration is unknown in equation (1). Considering that the measurement equation can measure the position of the object in real-time, and the thrown trajectory is known under the environment without natural wind, the average value of natural wind acceleration can be obtained by the observation value and one-step prediction value. At time $k$, the system observation value is $Z(k)$ from the measurement equation, and the position of the object and speed at time $k$ are obtained by the visual acquisition device.

$$X(k-1) = Z(k-1) \cdot H^{-1}$$  \hspace{1cm} (6)

Without considering the influence of natural wind, the one-step predicted position of the object can be obtained from the equation.

$$\hat{X}(k|k-1)|_{\alpha=0} = \phi X(k-1) + B_1 \cdot G$$  \hspace{1cm} (7)

Where $\hat{X}(k|k-1)|_{\alpha=0}$ represent the position and velocity of the object that is estimated from time $k-1$ when the object is not affected by natural wind. Therefore, the change of the thrown position within a single sampling period can be obtained by equations (6) and (7).

$$X(k) - \hat{X}(k|k-1)|_{\alpha=0} = Z(k-1) \cdot H^{-1} - \hat{X}(k|k-1)|_{\alpha=0}$$  \hspace{1cm} (8)

According to equation (8), thrown velocity at this moment can be expressed as

$$V(k) = \frac{Z(k-1) \cdot H^{-1} - \hat{X}(k|k-1)|_{\alpha=0}}{T} \hspace{1cm} V(k-1) = \frac{Z(k-1) \cdot H^{-1} - \hat{X}(k-1|k-2)|_{\alpha=0}}{T}$$  \hspace{1cm} (9)

The average acceleration can be obtained from equation (9)

$$a_a(k) = \frac{V_k - V_{k-1}}{T} = \frac{[Z(k) - Z(k-1)] \cdot H^{-1} - \hat{X}(k|k-1) + \hat{X}(k-1|k-2)}{T^2}$$  \hspace{1cm} (10)

2.3. Deduction of Natural Wind Variance

Based on the mean value of natural wind acceleration, the variance of natural wind acceleration can be deduced. The speed of natural wind generally shows a random change of lognormal distribution in office buildings and other places [13]. The acceleration of natural wind can be obtained by dividing the wind speed of natural wind by the sampling period. Since the speed of natural wind generally exhibits a random chance of the lognormal distribution and the sampling frequency is fixed, it can be approximated that natural wind acceleration generally exhibits a logarithmic random distribution of the state distribution.

In a short sampling period, the standard deviation changes in pace with the acceleration. Therefore, there is a certain proportional relationship between the standard deviation and acceleration. According
to the above analysis, the mathematical relationship between the standard deviation and the mean value of natural wind acceleration can be expressed as

\[
\sigma = \beta \cdot \left( a_n(k) - a_n(k-1) \right)
\]

(11)

Where \( \beta \) is the factor of scale\cite{14}. According to equation (4), the variance \( Q \) can be obtained by the standard deviation.

\[
Q = \begin{bmatrix}
\frac{1}{2} T^2 \cdot \sigma_x^2 & 0 & 0 & 0 & 0 & 0 \\
0 & T \cdot \sigma_y^2 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{2} T^2 \cdot \sigma_z^2 & 0 & 0 & 0 \\
0 & 0 & 0 & T \cdot \sigma_y^2 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{2} T^2 \cdot \sigma_z^2 & 0 \\
0 & 0 & 0 & 0 & 0 & T \cdot \sigma_z^2
\end{bmatrix}
\]

(12)

The range \( \beta \) is \( 1.19 < \beta < 1.55 \).

2.4. A Filtering Algorithm for Real-Time Updating

When the object is affected by natural wind, the estimated value of position and velocity of the object at time \( k \) can be deduced from the average value of position and velocity of the object at time \( k-1 \).

\[
\hat{X}(k|k-1) = \phi \cdot \hat{X}(k-1|k-1) + B_k \cdot G + B_z \cdot A_w
\]

(13)

The average value of the acceleration of natural wind in equation (13) is updated in real-time by equation (10), then the covariance matrix at time \( k \) can be derived from the covariance matrix at time \( k-1 \).

\[
P(k|k-1) = \phi P(k-1|k-1) \phi^T + \Gamma Q \Gamma^T
\]

(14)

Where \( Q \) is updated by equation (12) in real-time, the filter gain matrix at time \( k+1 \) can be obtained from equation (14).

\[
K(k) = P(k|k-1) h^T \left[ H P(k|k-1) H^T + R \right]^{-1}
\]

(15)

The one-step prediction value of the thrown position and speed at time \( k \) can be obtained by equations (13) and (15), and the covariance matrix is updated as follow.

\[
\hat{X}(k|k) = \hat{X}(k|k-1) + K(k) \cdot (Z(k) - H \cdot \hat{X}(k|k-1)) \quad P(k|k) = \left[ I - K(k) H \right] P(k|k-1)
\]

(16)

The system control quantity can be updated in real-time by equation (13), and the variance can be adjusted by equation (14), then the exact position of the object can be obtained by equations (15) and (16), as a result, the object out can be caught by the robot.

3. Simulation and analysis

3.1. Simulation of Research on the Thrown Trajectory in Natural Wind Environment

Without natural wind, the thrown trajectory is the object out that is only affected by gravity. According to figure 1, the simulation time, natural wind parameters, and thrown parameters are set in natural wind environment.

(1) Sampling period \( T \) is set as 0.02s, and the object without natural wind in 1-10 sampling periods (0.02s-0.2s), and the object is affected by natural wind in 11-20 sampling periods, that is 0.2s-0.4s.

(2) The mean value of two groups of natural wind acceleration (m/s\(^2\))
The direction of natural wind is from the z-axis to the top.
(0,0,0,0,0,0,0,0,0,0,0.3278,0.2311,0.1371,0.0051,0.0206,0.013,0.0487,0.1726,0.0873,0.0282)
The direction of natural wind is blowing down from the z-axis to upward.
(0,0,0,0,0,0,0,0,0,0,0.3726,0.5877,0.0257,0.1844,0.1603,0.2704,0.3348,0.3623,0.1599,0.1929)
(3) Table tennis is selected as the object whose parameters were about 0.04 meters in diameter and about 2.7 gram in mass.
(4) The initial angle of the object is 66°, the speed is 2m/s.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The two groups of thrown trajectory curves in natural wind.}
\end{figure}

In figure 2, it can be seen that the object starts from the eleventh cycle, and its z-axis direction deviates from the original trajectory by 0.011m and 0.015m. The deviation gradually increases afterward, and the deviation in the z-axis direction reaches a maximum value of 0.12m and 0.16m in the 18th cycle.

3.2. Simulation of Research on Mean and Variance of Natural Wind Acceleration
According to equation (10), the simulation results of the real wind acceleration mean and variance are updated in real-time.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Average acceleration is caused by the two groups of natural winds and estimated by the method.}
\end{figure}

It can be seen from figure 3 that the mean value of natural wind acceleration of the two groups is close to the true value based on the method of this paper. The maximum error between the average acceleration value and the true value estimated in the two groups of natural wind environment is only 0.012m/$s^2$ and 0.014m/$s^2$. 
Figure 4. The standard deviation of the two groups’ natural wind is estimated by the method.

As shown in figure 4, the maximum deviation between the estimated standard deviation and the true value is only 0.009m and 0.011m. Therefore, according to equations (10) and (12), the mean value and variance of the thrown acceleration caused by natural wind can be effectively estimated within the measurement period, so that the state equation of the object is described by equation (1).

3.3. Simulation of Research on Robot Catching the Object in Natural Wind Environment

(1) Kalman filter parameters:

The observed noise $V_i$ is zero-mean Gaussian white noise with an expectation of 0 and a variance of $R$. Covariance matrix is expressed as follows.

$$R = \begin{bmatrix} 0.05^2 & 0 & 0 \\ 0 & 0.01^2 & 0 \\ 0 & 0 & 0.01^2 \end{bmatrix}, \quad P(0) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

According to equations (11) and (16), the simulation result of robot catching the object is shown in the figure below.

Figure 5. The two groups of thrown trajectories in natural wind environment are based on the method in this paper.

In figure 5, it can be seen that in two groups of natural wind environments, the object deviates from its original motion trajectory by a maximum of 0.021m and 0.027m. Finally overlaps after 8 cycles to realize the object is captured by robot in natural wind environment.

4. Conclusion

A method of capturing the object in natural wind environment is proposed. The state equation and
measurement equation of the object in natural wind environment are studied. Meanwhile, with the established equation of measurement and state without natural wind, the average acceleration of the object caused by natural wind can be estimated. They have potential applications to improve the accuracy of the robot to capture the object in natural wind environment and expand the application range of robots to capture the object.

We only assume two fixed wind directions, however, the actual modeling and analysis of natural wind are very complex, the optical capture method is also worth studying.

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