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Indoor Surveillance Robot Controlled by a Smart Phone

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***Abstract*- As the smart phone becomes a remote processor for more functions in people daily lifes, the operators of the indoor survelience robots can be located anywhere if they have the smart phone. This paper presents the design of a mobile robotic system remotely controlled by a smart mobile phone via the Internet. A control client on the Android smart phone was the command center while the mobile robot was excuted to surveilence. The model predictive control method was applied on the side of the smart phone to generate an optimal sequence of the control commands. A network compensator was embeded on the robot to determine the current action of the robot. Experiments under different netwok conditions were carried out and analyzed for validation of the proposed system.**

Index Terms - Smart phone, Network time delay, Mobile surveillence robot.

I. INTRODUCTION

This paper presents a new robotic system for indoor surveillance where the robot can be remotely controlled by a smart phone in real time. The smart phone is used to remotely give the control commands to the robot for its movement, and receive the video frames of the surrounding environment from the camera mounted in the robot. The signal transmission between the robot and the smart phone is by internet. A model predictive controller is designed to compensate large time delay caused by the internet. Therefore, the usage of the smart phone makes the robot surveillance more flexible and convenient to control and allows the users to operate in different locations from the surveillance robot.

Recently mobile phone based robotic systems have attracted more and more attention. Ren C.Luo developed a security robot system which can be controlled by a cellular phone through GSM without any image information [1] . Yong-Ho Seo et al. developed a Touch-Based Control of a robot system that could remotely acquire information from the robot and control the robot by a touch event of the smart phone [2]. Sung Wook Moon introduced a phone operated control/monitoring system where video image could be transmitted from a spider robot to a smart phone. But the 200ms time delay between the camera and the mobile phone could not guarantee the efficiency of remote control [3].

Internet transmission is more complicated because it would cause larger time delays and more serious data dropouts. For the networked controlled systems, the time delay and disordering of the received packets induced by routers of data transmission and network traffic congestion are unavoidable, and can not be predicted accurately [4-6]. Liu et al. developed the networked predictive control (NPC) method [7] tackling long random time delays and serious data dropouts induced by the internet. However, it was difficult to individually measure the time delay for each trip unless there was synchronization for both the controller and plant side [8-10]. Hence a new NPC scheme based on round-trip delay measurement was proposed to avoid the individual time delay measurement [11-13]. Kühne et. al. presented an application of model predictive control to tackle the inaccuracy of trajectory tracking for mobile robot due to constraints on inputs or states that naturally arise [14]. We will, however, take advantage of the model predictive control in this paper to compensate the network time delay between the mobile robot and the smart phone.

The main contribution of this paper includes application of the model predictive control on a real-time mobile robot with a smart phone, and analysis in what practical scenarios this framework is more suitable.

The rest of the paper is organized as follows: Section 2 introduces the whole robotic system design. The experimental results and discussion are presented in Section 3. The concluding comments are presented in Section 4.

II. DESIGN OF ROBOTIC SYSTEM

A. Prototype Design

In this paper, an indoor mobile robot named “Robot-XD” was designed with the control pad of an Android smart mobile phone, Fig. 1. The robot hardware is mainly composed of an onboard computer, two DC motors with the encoders and a binocular camera. The remote control signals are transmitted via WIFI signal by a phone client/application on the smart mobile phone while the robot collects video information by cameras and then send the videos to the same client/application.

For the security purpose, the user name and corresponding

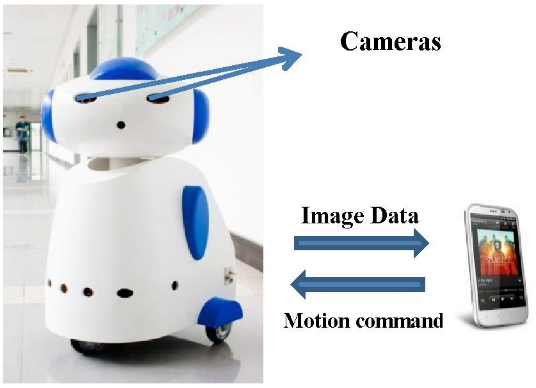

Fig. 1 Structure of the system

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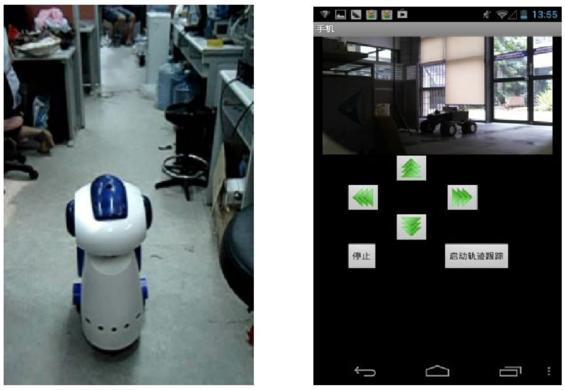

Fig. 2 Video image transfer and remote control on smart phone

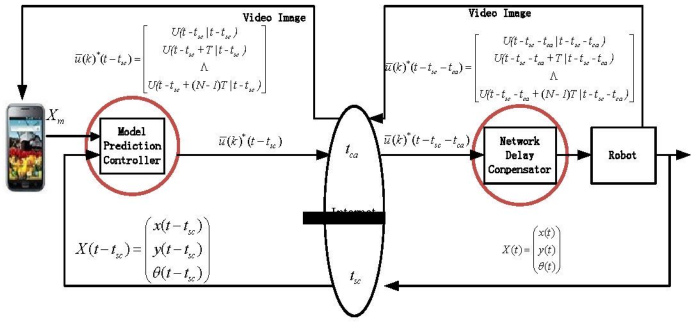

Fig. 4 Diagram of the mobile robot network predictive control system

password should be set up for each user. In order to enhance the speed of the image transmission between the smart mobile phone and the robot, the UDP services were selected rather than TCP services. Fig. 2 shows the interface of the phone client and the moving robot.

B. Controller Design with Network Delay Compensator

Although it is flexible and convenient for the mobile phone to control the robot, it has also introduced the time delay randomly because the mobile phone is usually in different location from the robot.

Computer network can be divided into three categories such as LAN, MAN and WAN according to different geographic locations and coverage [15]. Generally, the LAN is less than 10 km, which is usually used in a building, or between several buildings or inside a campus. The coverage of the MAN is larger than the LAN that covers a city typically from tens of kilometers to 100 kilometers. The WAN refers to all networks that are stronger than the MAN.

Three different sites have been selected to test how much of the time delays among the different networks (LAN/MAN/WAN) such as the company Huawei located in the same city as our lab, Shenzhen University Town located in the same campus as ours, Central South University located in another province. It was found out that the time delays were varied during the different time periods. Hence, according to the test results, the range of the time delay in LAN is mostly among 90~220ms while the maximum delay could reach up to about 420ms during occasional time periods (e.g. when the network was very busy). The delay of the MAN and WAN was about the same with the range of 180~280ms, and the maximum delay of about 550ms. Therefore, such long periods of network latency would apparently harm the efficiency of the remote control.

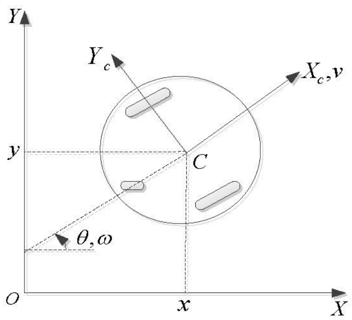

Fig. 3 The robot coordinate system.

As shown in Fig. 3, in the kinematic model of wheeled mobile robot (WMR) [16], the robot coordinate system is described by $X = [x, y, \theta]^T$. The control parameters of the robot is $u = [v, w]^T$, v and w represent the linear velocity and angular velocity of the robot.

To compensate the time delay, a model predictive controller was designed in this paper for the mobile robot remotely controlled by the smart phone. Fig. 4 shows the diagram of the compensated mobile robotic system.

According to Fig. 4, the round trip time delay (RTT) during the transmission of each data package includes the time delay of the control command, t_{ca}, and the time delay of the feedback package, t_{sc} [17]. The robot pose $X(t)$ and the current clock time at each sampling period (T) can be packed and sent to the smart phone through the Internet. When the smart phone receives this package, $X(t-t_{sc})$, the model predictive controller embedded in the phone will output the predictive sequence of the optimal control commands $\bar{u}(k)^*(t-t_{sc})$ based on the received package $X(t-t_{sc})$ and the reference X_m. This optimal control sequence is then sent to the robot with the time delay, t_{ca}, via the Internet [13]. The Network Delay Compensator embedded in the robot will select the proper command according to the current timestamp on the robot side from the newly received predictive control sequence $\bar{u}(k)^*(t-t_{sc}-t_{ca})$ and act it on the robot. If no newly control package is received during the sampling period, the command will be selected from the previous control sequence.

How to get the optimal control sequence $\bar{u}(k)^*$ will be presented in the rest of this section based on [14]. The robot motion model can be written as,

$$\begin{cases} x(k+1) = x(k) + v(k)\cos\theta(k)T \\ y(k+1) = y(k) + v(k)\sin\theta(k)T \\ \theta(k+1) = \theta(k) + w(k)T \end{cases} . \quad (1)$$

It can also be abbreviated as,

$$X(k+1) = f_c(X(k), u(k)) \quad (2)$$

This motion model will be used to get the sequence of the predictive control commands. Suppose the jth command of the sequence can be defined as:

$$X(k+j+1 \mid k) = f_c(X(k+j \mid k), u(k+j \mid k)) \quad (3)$$

The control purpose is to minimize the error caused by the Network latency between the prediction and the reference. Since solving the nonlinear optimal control at each sampling time needs high computational load [14], the linearization model prediction control (LMPC) is applied to transform the nonlinear optimization problem to the Quadratic Programming (QP) problem for real-time applications in this paper [18].

According to the Taylor series, a linear model of the system can be obtained with respect to the point (X_m , u_m) as,

$$\dot{X} \approx \dot{X}_m + f_{X,m}(X - X_m) + f_{u,m}(u - u_m) \tag{4}$$

where

$$X_m = \begin{pmatrix} x_m(t-t_{sc}) & \cdots & x_m(t-t_{sc}+(N-1)T) \\ y_m(t-t_{sc}) & \cdots & y_m(t-t_{sc}+(N-1)T) \\ \theta_m(t-t_{sc}) & \cdots & \theta_m(t-t_{sc}+(N-1)T) \end{pmatrix} \tag{5}$$

$$u_m = \begin{pmatrix} v_m(t-t_{ca}) & \cdots & v_m(t-t_{ca}+(N-1)T) \\ w_m(t-t_{ca}) & \cdots & w_m(t-t_{ca}+(N-1)T) \end{pmatrix}. \tag{6}$$

Define $\tilde{X} = X - X_m$ and $\tilde{u} = u - u_m$, then we can get

$$\dot{\tilde{X}} = f_{X,m}\tilde{X} + f_{u,m}\tilde{u} \tag{7}$$

where $f_{X,m}$ and $f_{u,m}$ are the Jacobian of f with respect to X and u, respectively. Define T is the sampling time, and the discrete-time model can be written as,

$$\tilde{X}(k+1) = A(k)\tilde{X}(k) + B(k)\tilde{u}(k) \tag{8}$$

$$A(k) = \begin{bmatrix} 1 & 0 & -v_m(k)\sin\theta_m(k)T \\ 0 & 1 & v_m(k)\cos\theta_m(k)T \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$B(k) = \begin{bmatrix} \cos\theta_m(k)T & 0 \\ \sin\theta_m(k)T & 0 \\ 0 & T \end{bmatrix} \tag{10}$$

Define the following vectors as,

$$\bar{X}(k+1) = \begin{bmatrix} \tilde{X}(k+1 \mid k) \\ \tilde{X}(k+2 \mid k) \\ \vdots \\ \tilde{X}(k+N \mid k) \end{bmatrix} \tag{11}$$

$$\bar{u}(k+1) = \begin{bmatrix} \tilde{u}(k \mid k) \\ \tilde{u}(k+1 \mid k) \\ \vdots \\ \tilde{u}(k+N-1 \mid k) \end{bmatrix} \tag{12}$$

Then $\bar{X}(k+1)$ can be written as,

$$\bar{X}(k+1) = \bar{A}(k)\tilde{x}(k \mid k) + \bar{B}(k)\bar{u}(k) \tag{13}$$

$$\bar{A}(k) = \begin{bmatrix} A(k \mid k) \\ A(k+1 \mid k)A(k \mid k) \\ \vdots \\ \varphi(k,2,0) \\ \varphi(k,1,0) \end{bmatrix} \tag{14}$$

$$\bar{B}(k) = \begin{bmatrix} B(k \mid k) & 0 & \cdots & 0 \\ A(k+1 \mid k)B(k \mid k) & B(k+1 \mid k) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \varphi(k,2,1)B(k \mid k) & \varphi(k,2,2)B(k+1 \mid k) & \cdots & 0 \\ \varphi(k,1,1)B(k \mid k) & \varphi(k,1,2)B(k+1 \mid k) & \cdots & B(k+N-1 \mid k) \end{bmatrix} \tag{15}$$

where

$$\varphi(k,j,l) = \prod_{i=l}^{N-j} A(k+i \mid k). \tag{16}$$

Hence an objective function is defined as,

$$\begin{aligned} \Phi(k) &= \sum_{j=1}^{N} \tilde{X}^T(k+j \mid k)Q\tilde{X}(k+j \mid k) + \sum_{j=1}^{N} \tilde{u}^T(k+j-1 \mid k)R\tilde{u}(k+j-1 \mid k) \\ &= \bar{X}^T(k+1)\bar{Q}\bar{X}(k+1) + \bar{u}^T(k)\bar{R}\bar{u}(k) \end{aligned} \tag{17}$$

where N is the prediction horizon and $Q \geq 0$, $R \geq 0$ are weighting matrices for the errors in the state and control variables, respectively.

Substituting Eq. (13) into Eq. (17), the objective function can be rewritten in a standard quadratic form:

$$\Phi(k) = \bar{u}^T(k)H(k)\bar{u}(k) + l^T(k)\bar{u}(k) + p(k) \tag{18}$$

$$H(k) = \bar{B}^T(k)\bar{Q}\bar{B}^T(k) + \bar{R} \tag{19}$$

$$l(k) = 2\bar{B}^T(k)\bar{Q}\bar{A}(k)\tilde{X}(k \mid k) \tag{20}$$

$$p(k) = \tilde{X}^T(k \mid k)A^T(k)QA(k)\tilde{X}(k \mid k) \tag{21}$$

The Hessian matrix $H(k)$ is always positive definite, and describes the quadratic part of the objective function while the vector $l(k)$ describes its linear part. As the $p(k)$ is independent on $\tilde{u}$, there is no influence on the optimal control sequence $\bar{u}(k)^*$. Thus, a new objective function can be defined as,

$$\Phi'(k) = \bar{u}^T(k)H(k)\bar{u}(k) + l^T(k)\bar{u}(k). \tag{22}$$

Then applying the standard procedures of solving QP problems, the optimal solution at each sampling time can be obtained as,

$$\bar{u}(k)^* = \arg\min_{\bar{u}}\{\Phi'(k)\}. \tag{23}$$

III. Experiments and Discussions

A. Methods and Procedures

In order to evaluate the performance of the compensated robotic system, a few experiments in three different network environments were carried out. In each experiment, the desired trajectory was planned on the mobile phone and the control commands were sent by the phone located in different sites from the robot. The robot was controlled to track the desired trajectory through the internet at our lab. The sampling period was 100ms and the number of the predict sequences was 10. Network delay inside our lab was very small because it was a small local network. The delay was mostly in the range of 30~60ms and the maximum value was about 150ms. Hence the 200ms additional delay was added to the random delay of the network in the lab to simulate the LAN environment on the campus. The 300ms additional delay was added to simulate the MAN/WAN environment. Two different reference trajectories were set up for evaluation. RF#1 consisted of straight line movement with the constant speed, the straight line movements with constant linear acceleration, and with constant linear deceleration, the short curves with constant angular and velocity accelerations. RF#2 contained half circle segments with constant angular and velocity accelerations.

Finally, the robot was controlled by the mobile phone via the MAN to track a practical surveillance route inside the lab. Fig. 5 shows the rectangular route in the laboratory where the pentagram is the starting point and the origin of the inertial coordinates.

B. Results and Discussion

Fig. 6 depicts the experimental results under the condition of LAN. The robot was tracking the RT#1. Tracking results with the compensated controller was compared to the results

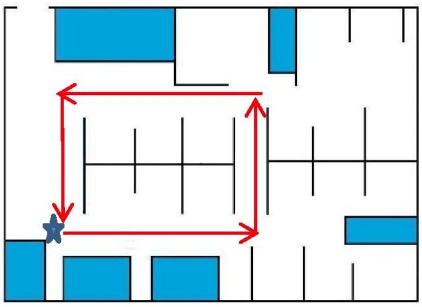

Fig. 5 Schematic diagram of the surveillance route in the laboratory.

without the delay compensation in Fig. 6. According to Fig. 6, the robot can track the reference trajectory precisely without the delay compensation in the LAN environment while the yaw angle swings. It was also observed that the speed of the robot was much smoother using the compensated controller than the one without the delay compensation.

Fig. 7 shows the tracking results of the robot under the network condition of the MAN with the same reference trajectory RF#1. Under this condition, the trajectory tracking accuracy of the robot was decreased greatly without the delay compensation. Meanwhile, the big time delay and slow convergence rate have led to the rapidly wiggling velocity. On the other hand, the performance with the time delay compensation was still good in terms of the robot pose and velocities even though with the large random time delay (Fig. 7 (a)). Fig. 8 shows the experimental results of tracking a different desired trajectory RF#2 under the network condition of MAN/WAN. Tracking results were consistent with the one for RF#1. The poor velocity tracking with large fluctuations have led to large tracking error and poor tracking performance. When the robot is in surveillance, it might be asked to execute different motion tasks such as straightforward moves, making turns, etc.. Therefore the network time delay should be compensated in a surveillance robot controlled via the Internet.

Fig. 9 shows the experimental results of tracking the surveillance route (shown in Fig. 5) under the network condition of MAN. This is more practical scenario where the user was somewhere in the city with his/her smart phone and the mobile robot was in their office or home. The route was totally about 20m long. The results showed that the proposed method can achieve the best tracking performance.

IV. Conclusions

This paper has presented the design of a new surveillance robotic system including the mobile robot and the smart phone. The network delay between the control commands and the robot has been compensated using model predictive control method. Experiments were conducted to validate and analyze the bound of the proposed design practically.

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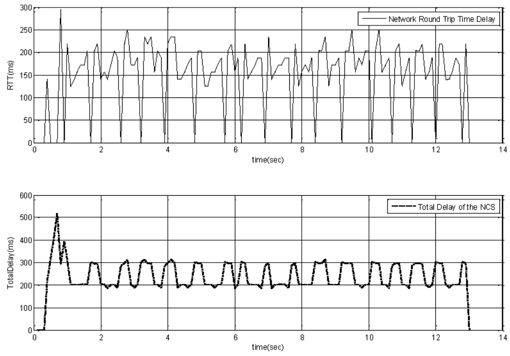
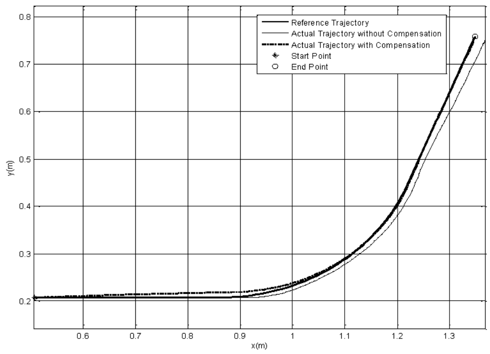
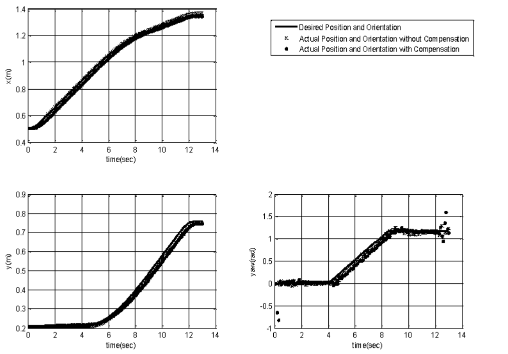


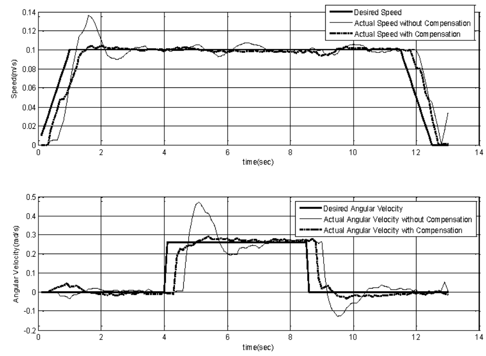
(a) Network delay and total time delay



(b) Tracking trajectories

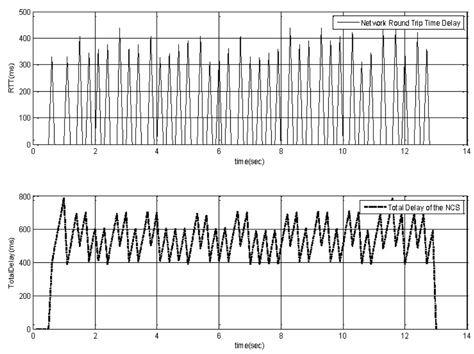


(c) Tracking errors in three coordinates

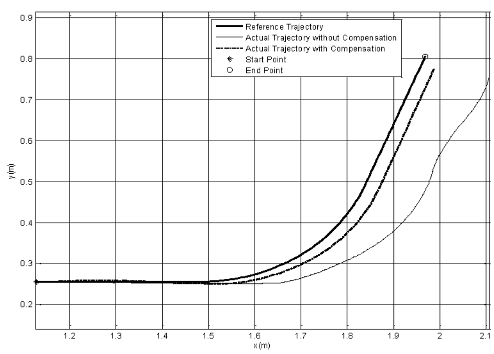


(d) Speed responses

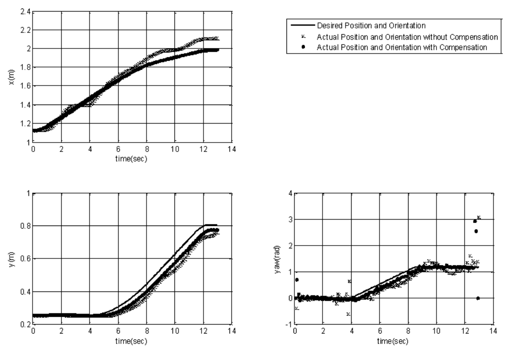
Fig. 6 Tracking results of RF#1 in the simulated LAN environment.



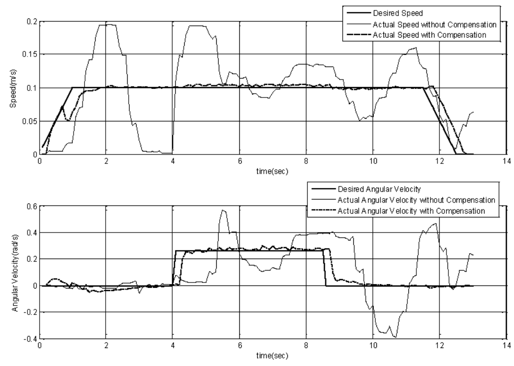
(a) Network delay and total time delay



(b) Tracking trajectories

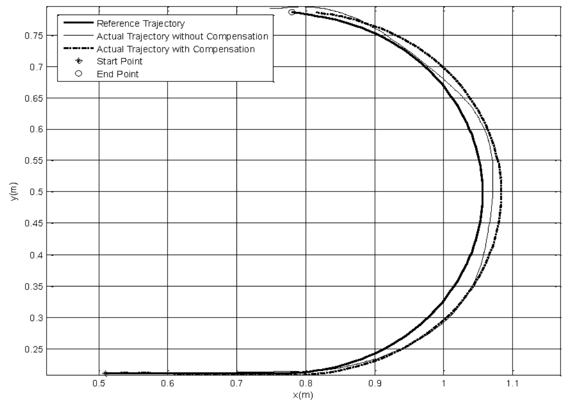


(c) Tracking errors in three coordinates

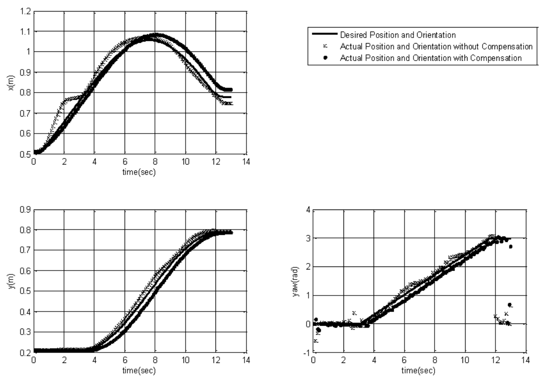


(d) Speed response

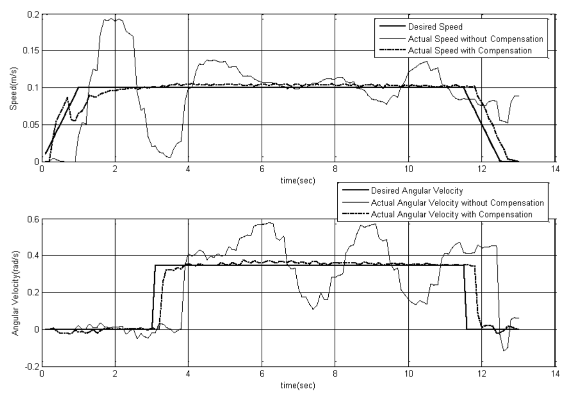
Fig. 7 Tracking results of RF#1 in the simulated MAN/WAN environment.



(a) Tracking trajectories

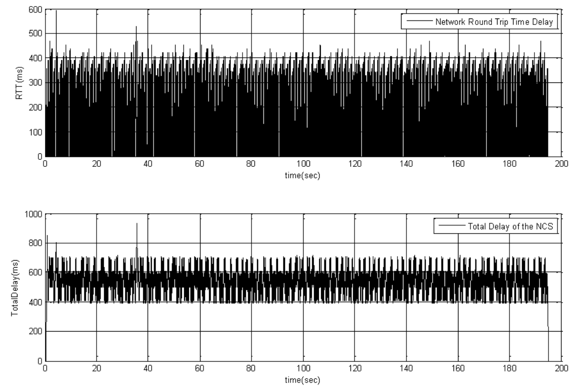


(b) Tracking errors in three coordinates

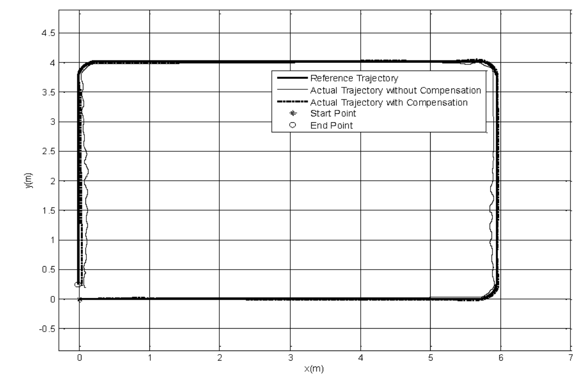


(c) Speed response

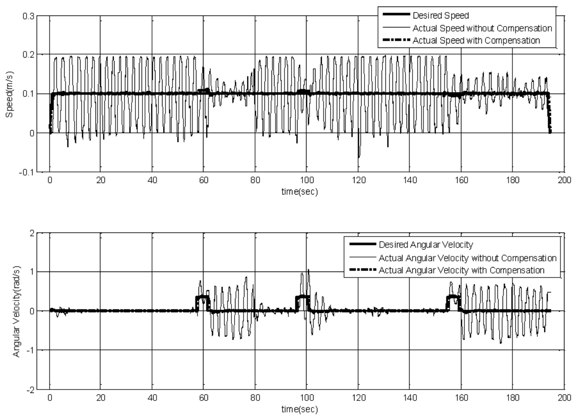
Fig. 8 Tracking results of RF#2 in the simulated MAN/WAN environment.



(a) Network delay and total time delay



(b) Tracking trajectories



(c) Speed response

Fig. 9 Tracking results of the surveillance route in the MAN environment.