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Remote control of an omnidirectional mobile robot with time-varying delay and noise attenuation☆

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ABSTRACT

This paper proposes a dead-time compensation control based on the filtered Smith predictor with an integral Linear Quadratic Regulator to remotely control an omnidirectional mobile robot subject to time-varying delay, sampling jitter and measurement noise. The filtered Smith predictor is used to preserve implementation simplicity, attenuate measurement noise and mitigate the performance degradation caused by the time-varying delay and sampling jitter. Implementation simplicity is achieved since the trade-off between robustness and closed-loop performance is handled from experimental tuning approach. Theoretical analysis is provided to show the benefits of the proposed compensation strategy. A set of experimental results with and without network-induced time-varying delay corroborate this analysis. Moreover, the relationship between measurement noise and the undesired time-varying delay effect is theoretically established to emphasize the benefits of the proposed approach. Practical results are presented in order to show that the proposed LQR/filtered Smith predictor strategy can be used in a NCS configuration providing good results with respect to trajectory tracking purposes despite its implementation simplicity.

1. Introduction

Computational burden and noise attenuation are key issues in mobile robot applications due to requirements such as hardware cost and sensor simplicity. Governed by its applications of control, it involves wireless communications, distributed computing, and higher-level controllers over a non-perfect communication channel. Networked Control Systems (NCS) is a natural way to deal with such systems due to their interconnectivity with sensors, actuators and communication devices distributed in the environment [1]. It is well known that Networked Control Systems provide wiring simplification, increased flexibility and overall cost reduction if compared with standard feedback control [2,3]. However, network-induced time-varying delays may impose significant performance degradation or even cause instability [4]. In the context of mobile robots, NCS performance degradation may be even more significant due to the undesired combination of networked induced delay and measurement noise.

Some frameworks for networked control systems are based on distributed processing, such as [5], where a distributed shared memory middleware (Real-Time Data Base - RTDB) decouples local processing from communication delays and provides fast access to remote data with age information. The framework presented by [6] separates the traditional elements of sensing, estimation, control, and actuation for a given system across a network and also allows sharing of information between systems. One of the most commonly used frameworks today is the ROS (Robot Operating System) [7], which offers a vast library to handle sensors and robots. ROS systems are based on so-called task nodes an it was originally created to distribute tasks, algorithms and also computational burden between different units throught local or wired communication. The performance changes when the nodes are connected via a wireless network, where the timing of the data delivery or excessive delay can have significant impact on the control loop [8]. Common to all approaches, the NCS paradigm presents several challenges as time-varying delay, non deterministic amount of latency, packet loss, and sampling jitter [4,9–12].

The filtered Smith predictor (FSP) has been used to deal with modeling error and measurement noise in the presence of constant delays [13]. In particular, the FSP was already used to control a mobile robot with a constant delay (local controller) for the sake of robust performance improvement [14]. However, FSP benefits were not analyzed in a NCS context with modeling error, measurement noise, time-varying delay and sampling jitter which are important sources of uncertainties in remote mobile robot control. To the best of the authors' knowledge, measurement noise attenuation was only studied by

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considering the FSP with constant delay [15] .

This paper proposes a simplified Linear-Quadratic Regulator (LQR)/FSP control strategy in order to perform the remote control of a mobile robot with measurement noise, time-varying delay, sampling jitter and modeling error. It is shown that FSP noise mitigation is important to reduce control signal variability which is significantly useful in the presence of time-varying delay. A framework based on ROS and an Omnidirectional Wheeled Mobile Robot (OWMR) are used, where both local and remote implementation are compared to evidence the benefits of the proposed controller. This paper has four main contributions: (i) to establish the relationship between performance degradation caused by network induced delay and measurement noise, (ii) to propose a simple dead-time compensation strategy that can be easily used to improve closed-loop performance in a NCS configuration, (iii) to formally demonstrate the benefits of the filtered Smith predictor in the context of NCSs and iv) to validate the theoretical analysis by comparing experimental results with and without networked induced delay. This comparison is possible due to the simplicity of the proposed strategy which can be embedded in a microprocessor. This simplicity is also desired in NCS applications [16] due to resources sharing and tuning simplicity, for instance. Moreover, the proposed idea is useful for practical application as the proposed tuning approach is based on the experimental data.

The paper is organized as follows. Section 2 presents the problem statement including the control strategy. In Section 3, two Dead-Time Compensation Control strategies are compared. Section 4 proposes a design procedure. Section 5 presents experimental results of the LQR/filtered Smith predictor strategy. Finally, the conclusions are drawn in Section 6.

2. Problem statement

NCS architectures have found wide acceptance in practice due to different reasons such as ease of installation, fault tolerance, economic benefits, or pure necessity (e.g. hazardous environments) [12]. With respect to mobile robots, this kind of strategy can also be used to simplify the embedded processor requirements, providing cheaper, lighter and smaller robots. The main drawback of the NCS comes from the additional challenges as time-varying delay and sampling jitter. This section is devoted to present a NCS configuration and to discuss its effect in terms of the remote control of a mobile robot.

2.1. Network control system setup

The network transmission delay is an important control problem due to its time-varying nature. Different control strategies can be used to attenuate the time-varying delay effect [12]. In this work, the remote controller is based on the ROS framework due to the implementation simplicity. This implementation strategy does not provide guarantees about the timing of operations because it is built on top of LINUX OS, which is not inherently real-time [17].

The sequence of closed-loop control events is indicated in Fig. 1. In the proposed wireless closed-loop architecture, the control cycle is triggered at the instant kT where T is the cycle interval and $k \in \mathbb{N}$. Firstly, a new control action is sent from the remote controller to the mobile robot. This new control action, which was previously computed at $(k-1)T + d_{k-1}$, is effectively updated at $kT + l_k$ where l_k represents the delay from the trigger instant (kT) until the effective control change. Note that l_k is composed by multiple sources: transmitter processing delay, transmission delay, and receiver processing delay. Then, a new sample is measured at $kT + l_k$, which is used at $kT + d_k$ in order to compute the next control action. A desired output variable is described by $x(t)$ and its measured value without noise can be represented by $x(kT + l_k)$.

The next control value can be expressed by $\tilde{u}_k = \kappa(x(kT + l_k))$ where $\kappa(\cdot)$ denotes an arbitrary control law. Note that $\tilde{u}_k = \kappa(x(kT + l_k))$ is effectively updated at $(k+1)T + l_{k+1}$. In this strategy, the time-varying delay between measurement instant and control update is given by $T + l_{k+1} - l_k$ for a given control value u_k. In the ideal situation, without time-varying delay ($l_{k+1} = l_k$), the dead-time would be equal to a single sampling period. Also note that T should be defined in order that $d_K < T, \forall k \geq 0$, to guarantee that a new control is transmitted at every instant kT.

Despite the time-varying nature of this delay, a linear time-invariant model with additive uncertainties can be used to describe this uncertain system. The main idea is to adopt a linear time-invariant strategy due to implementation simplicity. However, despite the control law simplicity, challenges such as time-varying delay, model uncertainty, neglected nonlinearities and measurement noise should be mitigated by using this linear strategy.

2.2. Model uncertainties

The NCS effect can be described by using a linear state-space model with additive disturbances in order to design and analyze a linear control law. Consider the following state-space description:

$$\dot{x}(t) = (A + \widehat{A})x(t) + (B + \widehat{B})u_c(t) + f(x(t)), \tag{1}$$

$$y(t) = x(t) + \eta(t), \tag{2}$$

where $A \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times m}$ describe the nominal model, $\widehat{A} \in \mathbb{R}^{n\times n}$ and $\widehat{B} \in \mathbb{R}^{n\times m}$ represent parameter uncertainty, $f(x(t))$ is a nonlinear vector function ($\mathbb{R}^n \to \mathbb{R}^n$) which represents friction effect, $x(t) \in \mathbb{R}^n$ is the state vector without measurement noise, $\eta(t) \in \mathbb{R}^n$ describes the measurement noise with null mean, $y(t) \in \mathbb{R}^n$ represents the measured output and $u_c(t) \in \mathbb{R}^m$ is the control signal which is effectively applied at the instant “t”.

It is shown in Appendix A that an equivalent time-invariant representation can be obtained as follows:

$$x_{k+1} = A_d x_k + B_d u_{k-1} + w_k, \tag{3}$$

$$y_k = x_k + \eta_k, \tag{4}$$

where $A_d = e^{AT}$, $B_d = \int_0^T e^{A(T-\tau)} B d\tau$, $x_k = x(kT)$, $y_k = y(kT)$, $\eta_k = \eta(kT)$ with $\tilde{u}_{k-1} = \kappa(x(kT - T + l_k))$, and $u_{k-1} = \kappa(x(kT - T))$. Moreover, the additive disturbance w_k can be respectively decomposed into sampling jitter, transmission delay, neglected friction, and model uncertainty components as follows:

$$w_{s,k} = B_d[\kappa(x(kT + l_k)) - \kappa(x(kT))], \tag{5}$$

$$w_{t,k} = \int_0^{l_k} e^{A(T-\tau)} d\tau B[\tilde{u}_{k-2} - \tilde{u}_{k-1}], \tag{6}$$

$$w_{f,k} = \int_0^T e^{A(T-\tau)} f(x(kT + \tau)) d\tau, \tag{7}$$

$$w_{u,k} = \int_0^T e^{A(T-\tau)} (\widehat{A} x(kT + \tau) + \widehat{B} u_c(kT + \tau)) d\tau, \tag{8}$$

with $w_k = w_{s,k} + w_{t,k} + w_{f,k} + w_{u,k}$.

Details are presented in Appendix A, but this result shows that transmission delay effect can be mitigated by reducing the difference between two subsequent control actions ($\|\tilde{u}_{k-2} - \tilde{u}_{k-1}\|$). Moreover, this equivalent description is important to emphasize that a simple LTI control strategy can be used to remotely control robot if disturbance effect is correctly handled. The robot model used during this article is described in Appendix B.

3. Dead-time compensation control

The proposed NCS configuration imposes a constant delay as pointed out in Eq. (3). A dead-time compensation (DTC) strategy can be used to deal with this constant delay in order to improve closed-loop performance. In this section, two DTC strategies are compared with