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Predictive control approaches for bilateral teleoperation☆

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ABSTRACT

Performance and stability are both affected due to time delay in bilateral teleoperation. Recent researches have reported the effectiveness of applying predictive control approaches to cope with the time delay effect which improve both stability and transparency. In this regard, this article aims to provide a systematic review of the predictive control approaches in bilateral teleoperation. The survey also tries to compare and assess the main features and properties of the predictive control schemes as much as possible. The survey elaborates initially the most common schemes and then qualitative and quantitative comparisons along with discussions are made with respect to stability, transparency, and robustness.

1. Introduction

Teleoperation has a history of over 60 years and significant research has been conducted in last several decades to address the key issues i.e., stability and transparency in bilateral teleoperation. Variety of teleoperation control schemes, in this regard, have been proposed so far. These schemes help humans to perform challenging and hazardous task in the remote environment such as space, undersea, surgical operations, nuclear stations etc., (Hokayem & Spong, 2006; Sheridan, 1995).

The two brilliant surveys Hokayem and Spong, 2006 and Arcara and Melchiorri, 2002 give in-depth details, comparisons, and analyses of the control schemes ranging from supervisory control, scattering theory, passivity, frequency domain techniques, adaptive and predictive methods for teleoperation systems till the mid-2000 (mid of last dacade). In recent years, some approaches were introduced which can also be categorized for teleoperation control schemes and their applications such as passivity-based control (Nuño, Basañez, & Ortega, 2011; Seo et al., 2011), wave variable – based control (Sun, Naghdy, & Du, 2014), robust control (Alfi & Farrokhi, 2008b; Khosravi, Alfi, & Roshandel, 2013; Seo, Kim, Kim, Ahn, & Ryu, 2011), adaptive control (Nuño, Ortega, & Basañez, 2010), impedance control (García-Valdovinos, Parra-Vega, & Arteaga, 2007; González, De Leon, Guerra, & Parra, 2011), force reflecting control (Alfi & Farrokhi, 2008a; Polushin, Peter, & Lung, 2007), synchronization and optimal performance of teleoperation systems etc., (Alfi, Khosravi, & Lari, 2013; Chopra, Spong, & Lozano, 2008; Shokri-Ghaleh & Alfi, 2014a, 2014b). Furthermore, some more related important surveys and comparisons were also recently reported in Passenberg, Peer, and Buss, 2010; Rodriguez-Seda, Lee, and Spong, 2009; Sun et al., 2014. In early 2000s, many predictive control applications to bilateral teleoperation drew the attention of teleoperation researchers due to their ability to compensate the effect of large time delays, which results in improved performance and stability. These predictive control approaches are not new in control theory. These approaches in early stages were utilized for the process control for time delayed systems introduced by O.J. Smith in 1957 (Smith, 1957) and later for teleoperation in 1989 (Buzan & Sheridan, 1989). However, their significant evolution in teleoperation has occurred in the last decade. The above mentioned surveys (Arcara & Melchiorri, 2002; Hokayem & Spong, 2006) do not cover much of the latest and prominent predictive control approaches as most of the approaches were introduced in the mid-2000s. This paper, therefore, aims to provide a systematic review of the predictive control approaches in bilateral teleoperation. The survey also tries to compare and assess the main features and properties of the predictive control schemes as much as possible.

The predictive control approaches applied in haptic teleoperation (Antonello, Daud, Oboe, & Grisan, 2012; Arioui, Kheddar, & Mammar, 2002a; Bemporad, 1998; Buzan & Sheridan, 1989; Casavola, Mosca, & Papini, 2006; Ching & Book, 2006; Fite, Goldfarb, & Rubio, 2004; Ganjefar, Momeni, & Sharifi, 2002;

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Huang & Lewis, 2003; Iqbal & Roth, 2006; Katsura & Ohnishi, 2006; Kawashima, Tadano, Sankaranarayanan, & Hannaford, 2008; Li & Song, 2007; Minh & Hashim, 2010; Mitra & Niemeyer, 2008; Munir & Book, 2002; Pan, Canudas-de-Wit, & Sename, 2006; Sheng & Spong, 2004; Sirouspour & Shahdi, 2006b; Slama, Trevisani, Aubry, Oboe, & Kratz 2008; Smith & Hashtrudi-Zaad, 2006; Smith & Jensfelt, 2010; Uddin, Park, & Ryu, 2016a; Yang, Li, Chen, & Yi, 2014; Yoon et al., 2004; Yoshida & Namerikawa, 2008) are mostly model-based approaches. These approaches can be majorly categorized into three groups: (i) Smith predictor (SP), (ii) Model-based predictor (MBP), and (iii) Model/Generalized predictive control (MPC/GPC). They are utilized together with wave variables (WV) (Arioui et al., 2002a; Ching & Book, 2006; Ganjefar et al., 2002; Kamrani, 2012; Munir & Book, 2002), neural networks (NN) (Chen, Quan, & Xia, 2007; Choi & Jung, 2009; Huang & Lewis, 2003; Minh & Hashim, 2010; Smith & Hashtrudi-Zaad, 2006), frequency domain techniques (FDT) (Fite et al., 2004; Slama et al., 2008), quadratic cost function (QCF)/optimization (Bemporad, 1998; Chen, Xi, Wang, Li, & Tang, 2008b; Shahdi & Sirouspour, 2009c; Sheng & Spong, 2004; Sirouspour & Shahdi, 2006a, 2006b; Slama et al., 2008; Yang et al., 2014), energy-bounding approach (EBA) (Uddin et al., 2016a; Uddin, Park, & Ryu, 2016b; Uddin, Park, Baek, & Ryu, 2013), time domain passivity control (TDPC) (Iqbal & Roth, 2006; Kawashima et al., 2008), proportional-derivative (PD) (Yoshida & Namerikawa, 2008; Yoshida et al., 2008), etc. As far as the fundamental differences between them are concerned, the SP (Ganjefar, Momeni, Sharifi, & Beheshti, 2003; Smith & Hashtrudi-Zaad, 2006; Smith, 1957; Uddin et al., 2016a) incorporates the slave haptic data (position/force) explicitly in its structure (as a requirement to effectively cancel the estimated and delayed dynamics). However, the MBP (Buzan & Sheridan, 1989; Uddin et al., 2013) normally does not consider it, but sometimes it is considered depending upon the requirement of a particular control law (but not for the cancellation of estimated and delayed dynamics like SP) (Minh & Hashim, 2010; Pan et al., 2006). On the other hand, MPC may have either SP or MBP structure and necessarily is followed by any optimization technique such as QCF, Controlled Auto-Regressive and Integrated Moving Average (CARIMA), etc., (Bemporad, 1998; Chen et al., 2008b; Shahdi & Sirouspour, 2009c; Sheng & Spong, 2004; Sirouspour & Shahdi, 2006a, 2006b; Slama et al., 2008; Yang et al., 2014). There are also limited number of model-free predictive approaches (or trajectory extrapolating predictors) (Clarke, Schillhuber, Zaeh, & Ulbrich, 2008; Prokopiou, Tzafestas, & Harwin, 1999), which predict the future position/force trajectories learned from the past histories (or by extrapolation) of force and position data.

In terms of the range and the location of model estimation, SP-based approaches in Bowthorpe, Tavakoli, Becher, and Howe, 2013; Ching and Book, 2006; Fite et al., 2004; Ganjefar et al., 2002; Huang and Lewis, 2003; Munir and Book, 2002; Slama et al., 2008; Smith and Hashtrudi-Zaad, 2006; Uddin et al., 2016a; Uddin et al., 2016b; Wang, Xu, Jia, and Liu, 2007 estimate either slave/environment models or environment models only on the master side. Meanwhile, MBP/MPC approaches in Antonello et al., 2012; Arioui et al., 2002a; Bemporad, 1998; Bratt, Smith, and Christensen, 2006; Buzan and Sheridan, 1989; Casavola et al., 2006; Katsura and Ohnishi, 2006; Kawashima et al., 2008; Lee, Payandeh, and Trajkovic, 2010; Li and Song, 2007; Mitra and Niemeyer, 2008; Mobasser and Hashtrudi-Zaad, 2007; Pan et al., 2006; Shahdi and Sirouspour, 2009c; Sirouspour and Shahdi, 2006a, 2006b; Smith and Hashtrudi-Zaad, 2006; Xiao-hui, He-sheng, and Guo-ping, 2011; Yang et al., 2014; Yoon et al., 2004 use estimated models of the human, master, slave and/or environment. More categorically, MBP/MPC approaches predict (i) the slave states on master side (Casavola et al., 2006; Kawashima et al., 2008; Mitra & Niemeyer, 2008; Mobasser & Hashtrudi-Zaad, 2007; Smith & Hashtrudi-Zaad, 2006; Yoshida & Namerikawa, 2009), (ii) master states on the slave side Prokopiou et al., 1999; Slawinski & Mut, 2007), (iii) operator decision on slave side (Nieto, Slawiñski, Mut, & Wagner, 2012) or master side (Slawiñski & Mut, 2010; Smith & Jensfelt, 2010), (iv) both master and slave states simultaneously on the other ends (Lee et al., 2010; Pan et al., 2006; Yoshida & Namerikawa, 2008; Yoshida et al., 2008), (v) both master/operator and slave/environment dynamics on centralized master (or slave) side (Sirouspour & Shahdi, 2006a, 2006b), or on decentralized master and slave sides (Shahdi & Sirouspour, 2009c), (vi) energies at master side (Iqbal & Roth, 2006) in order to avoid the delayed information and compensate the delay effect.

Some of the MBP/SP approaches such as (Katsura and Ohnishi, 2006; Li and Song, 2007; Mitra and Niemeyer, 2008; Uddin et al., 2013 Uddin et al., 2016a; Uddin et al., 2016b) can be further categorized into the virtual environment model-based predictor (VE-MBP) (Katsura & Ohnishi, 2006; Li & Song, 2007; Mitra & Niemeyer, 2008; Uddin et al., 2013) and the virtual environment-SP (VE-SP) (Uddin et al., 2016a; Uddin et al., 2016b). In these approaches, either only a geometric model is used (Katsura & Ohnishi, 2006) or a geometric model along with a dynamic model is superimposed over real video images or virtual environments at the master side through augmented reality (Li & Song, 2007) or both estimated geometric and dynamic information is used at the master side (Mitra & Niemeyer, 2008; Uddin et al., 2013; Uddin et al., 2016a; Uddin et al., 2016b).

One of the most important factors affecting stability and transparency in bilateral teleoperation is the time delay in the communication channel. The delay may be either small or large and also either constant or time-varying. Moreover, there may be data losses and may suffer communication blackout during teleoperation. These features are either explicitly predicted (Mirfakhrai & Payandeh, 2002; Witrant, Canudas-de-Wit, & Georges, 2003) or simplified as a constant delay without any data losses (Fraisse & Leleve, 2003; Wang et al., 2007).

This paper reviews the main ideas and features of the most common and prominent predictive control techniques for teleoperation published in the literature based on SP, MBP, and/or MPC/GPC used with WV, NN, FDT, Lyapunov, LQG, TDPC, PD, EBA, Passivity etc. In addition, the survey addresses the utility of different predictive control approaches with respect to *a priori* knowledge of models (human, master, slave and environment), predicted signals (position/force), prediction side (location i.e., master/slave), adaptive/non-adaptive nature, task scenarios (either simulated or experimented for validation). Moreover, it also provides qualitative and quantitative comparisons along with detailed discussions of prominent schemes with respect to stability, transparency, and robustness.

The paper is organized as follows; Section 2 formulates the teleoperation systems. Section 3 states the definitions and the description of the prominent predictive teleoperation schemes. Section 4 is composed of detailed qualitative and quantitative comparisons and discussions between these predictive approaches. Section 5 makes some conclusions.

2. Teleoperation systems

This section presents basic architectures of the bilateral teleoperation system, basic governing equations, definitions of transparency, stability (passivity) to explain the key features of the bilateral teleoperation.

2.1. Systems and dynamics

The following definitions of variables are given in the nomenclature below: