Automation in Construction 51 (2015) 46–58

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A practical interface for coordinated position control of an excavator arm

Ryder C. Winck [a,*], Mark Elton [b], Wayne J. Book [c]

[a] Mechanical Engineering, Rose-Hulman Institute of Technology, USA
[b] HUSCO International, Waukesha, WI, USA
[c] Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ARTICLE INFO

Article history:
Received 20 June 2013
Received in revised form 17 November 2014
Accepted 15 December 2014
Available online 8 January 2015

Keywords:
Coordinated control
Human–machine interface
Kinematically similar joystick
Hydraulic manipulators
Excavators
Human factors

ABSTRACT

This paper presents a new hand controller interface that addresses practical challenges to implementing coordinated position control (CPC) for an excavator arm. The new interface uses a hybrid control scheme with closed-loop CPC of the excavator arm and open-loop flow control of the swing. CPC is achieved using a joystick that is kinematically similar to the excavator arm. The kinematically similar joystick motion is planar. Thus, it can be mounted vertically, matching the excavator arm, or horizontally, which has many advantages, such as reduced operator fatigue. The new interface is compared to a conventional interface in a human subject experiment using a dynamic excavator simulator. The results demonstrate similar improvements in spoil removed and fuel efficiency as previous CPC approaches while being more practically designed. Although the design is for an excavator, the concepts presented can apply to a range of hydraulic manipulators.

1. Introduction

This paper proposes a new hand controller interface that addresses many of the practical challenges to implementing coordinated position control (CPC) on hydraulic machines. A human subject experiment demonstrates the use of the new hand controller interface and provides initial validation that the new interface, while being more practical to implement, maintains the performance benefits of CPC. Hydraulically actuated manipulators are used on many machines, including excavators, backhoes, concrete pump trucks, and telescopic handlers, and in a number of industrial applications, such as construction, forestry, mining, and agriculture. Despite being commonly used in industry for many years, these manipulators are challenging for novices to use, and, even after becoming experts, operators continue to make mistakes due, among other factors, to the high cognitive load required to control the manipulators [1]. The high cognitive load is due in part to the hand controller interface. Conventionally hydraulic manipulators are operated using joint control, which is difficult to learn and use. For example, on an excavator, the four degrees-of-freedom (DOFs) are independently controlled using the canonical directions of two joysticks, as shown in Fig. 1. In previous work, Elton and Book [1–4] showed significant performance gains using a CPC interface when compared to a traditional interface in a simulated trenching task. In spite of these performance gains, many challenges remain to practically implement CPC on an excavator or similar machine. Four challenges will be specifically discussed in this paper: (1) potential for greater operator fatigue and operator comfort; (2) loss of accuracy due to position scaling; (3) potential for unwanted machine motion; and (4) the operator's lack of knowledge of the commanded position. These challenges are manifested in a specific way for hydraulic machines, but they are generally applicable for many applications of CPC [15,26,27]. A fifth challenge that will not be directly addressed in this paper is biodynamic feedthrough.

Although addressing these practical aspects is imperative, the new interface must also continue to provide a performance benefit. The human subject experiment presented in this paper shows that the new interface does not lose the performance benefits of CPC in an effort to be more practical. It also provides an initial indication of potential performance benefits of the new interface compared with a conventional interface. As in previous work [1,6,7], the subjects' performance is based on specific task metrics. The metrics used in this paper relate to those in Elton and Book [1] and are the amount of spoil removed over a given period of time during a trenching task and also the amount of spoil removed for a given amount of fuel. The result is a new interface that maintains the benefits of CPC while addressing impediments towards its implementation in hydraulic machinery. After the background for this research and some related work is discussed, Section 4 describes the new interface and discusses some of the practical benefits of the interface compared with previous approaches to CPC. Sections 5 and 6 describe the experiment and results, and Section 7 discusses the results.

Abbreviations: CPC, coordinated position control; KSJ, kinematically similar joystick.

* Corresponding author at: 5500 Wabash Ave., Terre Haute, IN 47803, USA. Tel.: +1 812 877 8098.
E-mail address: winckrc@rose-hulman.edu (R.C. Winck).

http://dx.doi.org/10.1016/j.autcon.2014.12.012
0926-5805/

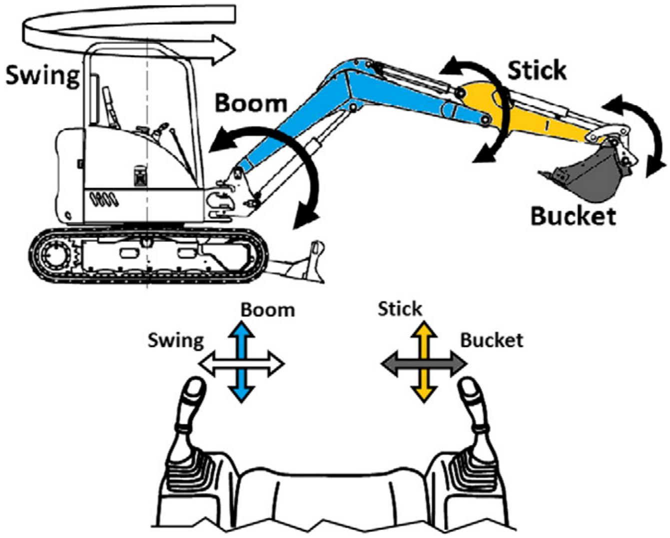

Fig. 1. A conventional interface using joint control of a hydraulic excavator.

2. Background

Early hydraulic manipulators used levers or pedals to directly actuate the valves controlling the manipulator. Thus, a separate lever was used for each degree of freedom (DOF), and the motion of the lever was directly linked to the flow into the cylinder. Pilot-operated valves were later added that allowed for multi-directional joysticks, shown in Fig. 1, to be used to control the various DOFs. The multi-directional joystick improved on the lever design because operators could more easily actuate all of the joints simultaneously and because some of the DOFs were more physically correlated. The multi-directional joystick has become the standard for many different hydraulic machines and will be referred to as the conventional interface in this paper. Electro-hydraulic controllers were introduced where the operator moved a joystick that electronically actuated the valves controlling the manipulator. The move to electro-hydraulic joysticks permitted the joysticks to be reduced in size, exerted a reduced load on operators, and permitted more variations to their design. Yet today, the basic concept of the conventional interface has remained the same. The longevity of the multi-directional joystick design can be attributed to a number of factors, such as economic, technologic capability, ergonomic, and industry inertia. Thus, any new interface must demonstrate significant performance improvements to provide incentive for manufacturers to change their design and for operators to relearn a new interface.

In spite of this industry inertia, there remains potential to significantly improve the intuitiveness of the human–machine interface for hydraulic machines. Although the conventional interface has been used for many years, and expert operators are very capable, it requires many years and special training for a person to become an expert operator [1,5]. With the conventional interface, the operator provides an open-loop flow command to each manipulator joint. Therefore, in the absence of large disturbance forces relative to the system pressure, this flow command is roughly equivalent to commanding the joint velocity of the manipulator, or joint rate control. For the purposes of this paper, this will be referred to as joint flow control. To control a manipulator, operators must mentally perform the inverse kinematics of the manipulator in their heads. For these reasons, many researchers have sought to improve on the control interface to make the machines more intuitive to operate [1–3,6–14]. Below is a brief discussion of some of these efforts.

3. Related work

A number of researchers have explored the use of coordinated control for hydraulic manipulators [1–3,6–14]. In contrast with the joint flow control described above, coordinated control relieves the operator from the necessity of mentally performing inverse kinematics by using computer control to convert the operator's command inputs into joint commands that actuate the valves. Coordinated control does require closed-loop control of the manipulator joints, but has been shown to lead to significant increases in operator performance. For example, Lawrence et al. [6], Parker et al. [8], and Wallersteiner et al. [7] applied coordinated control along with haptic feedback to an excavator, log-loader, and feller-buncher. Their experimental results demonstrated the advantages of both on these machines. Lawrence et al. [6] showed that coordinated control reduced the incidence of butt damage during cutting using a feller-buncher. Wallersteiner et al. [7] compared coordinated control with a conventional interface for a log loader using both novice and expert operators and evaluated performance using a time trial of placing logs in designated cradles. They showed that coordinated control greatly reduced the time required for novices to complete the task, and that, with limited training, expert operators could complete the task with the new controller with equal proficiency compared to using the conventional interface. Parker et al. [8] focused on the control of force for a feller-buncher. During the same time period, Hadank et al. and Allen et al. [11, 12] filed patents for a coordinated rate control system for an excavator. More recently, Yoon and Manurung [14] applied coordinated rate control to a hydraulic backhoe. They compared it with a conventional interface in flattening and digging tasks and found that novice operators performed better in these tasks with coordinated control but that the performance difference declined as the number of trials increased. However, their only experimental results used a kinematic simulation with a velocity limit and the machine dynamics have been shown to have a strong effect on interface performance [15]. Coordinated position control (CPC) has been shown to be more effective than coordinated rate control (CRC) for a variety of manipulators and tasks, the exception being manipulators with large workspaces and slow dynamics, which are characteristic of hydraulic manipulators [15,16]. However, both CPC [1–3,6–10,17–20] and CRC [11–14] have been demonstrated on hydraulic equipment. Kim's approach used sensors placed on the operator's arm for CPC of a teleoperated excavator [17]. Lee and Lee patented a hand controller that can provide CPC for an excavator arm [18]. In a later patent application, Hodgson built on the work of Lee and Lee by making the hand controller kinematically similar to the excavator arm [19]. A similar patent application to Hodgson has been published recently by Lyu et al. where the hand controller is a miniature replica of the excavator arm [20]. The new interface presented in this paper also uses a kinematically similar joystick, but unlike these patents, it is used within a hybrid control scheme, which restricts joystick motion to a plane. Hybrid control schemes have been used for large workspace manipulators to permit the benefit of position control while reducing the adverse scaling inaccuracies [1,21–23]. Position scaling has also been addressed through the use of clutch mechanisms and adjustable position scales [32]. It can allow for selective fine control when the task calls for such precision.

Previous work by Elton and Book [1] compared CPC and a hybrid of CPC with a conventional interface for a hydraulic excavator. They used a Geomagic Phantom Premium haptic device [24] for both CPC and a hybrid of CPC. The hybrid control used CPC to control the boom, stick, and bucket of the excavator and joint flow control for the swing of the cab. Overall, that was still a coordinated control scheme in a cylindrical coordinate system with open-loop flow control of the azimuth, whereas the CPC alone is in Cartesian coordinates. They showed that CPC allowed novice operators to remove more spoil over a given period of time and for a given amount of fuel in a simulated digging task than either the hybrid of CPC or the conventional interface. In addition to demonstrating that performance improvement, they also identified some challenges to CPC's practical implementation on a hydraulic machine. Subjects found the Phantom device to be less comfortable and more fatiguing than traditional joysticks, largely due to the need to keep their arm elevated. They also commented that the interface was too sensitive to small motions and that it was more difficult to hold the excavator arm