Robotics and Autonomous Systems 73 (2015) 68–77

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

A generalized control framework of assistive controllers and its application to lower limb exoskeletons

Sehoon Oh [a], Eunyoung Baek [a], Seok-ki Song [a], Samer Mohammed [b], Doyoung Jeon [a], Kyoungchul Kong [a,*]

[a] Department of Mechanical Engineering, Sogang University, 121-742 #1 Shinsu-dong Mapo-gu, Seoul, South Korea
[b] Laboratoire Images, Signaux et Systèmes Intelligents (LISSI) at the Université Paris-Est Créteil, France

HIGHLIGHTS

- A generalized control framework is proposed to incorporate the various assistive control methods in one general controller structure.
- The proposed control framework enables the continuous and smooth switching of assistive control algorithms.
- The proposed control framework makes it possible to analyze the stability of the overall control loop.
- The proposed method is implemented into a lower-limb exoskeleton robot and is verified by experimental results.

ARTICLE INFO

Article history:
Available online 18 October 2014

Keywords:
Lower limb exoskeleton
Assistive control
Hybrid control
Stability analysis
Gait phase
Impedance control
Disturbance observer
Impedance reduction control
Series elastic actuator

ABSTRACT

Various control methods have been studied for the natural assistance of human motions by exoskeletal robots, i.e., wearable robots for assisting the human motions. For example, impedance control and compliance control are widely used for controlling interaction forces between a human and a robot. When an accurate measurement of the human muscular force is available (e.g., electromyography), a direct use of the estimated human joint torque is possible in the control of an assistive robot. The human motions in a daily living, however, are so complex that they are constituted by multiple phases, such as walking, sitting, and standing, where the walking can be further categorized into multiple sub-phases. Therefore, a single control method cannot be the best option for all the motion phases; a switch in the control algorithms may be necessary for assisting human movements in multiple motion phases. In this paper, a generalized control framework is proposed to incorporate the various assistive control methods in one general controller structure, which consists of Feedforward Disturbance Compensation Control, Reference Tracking Feedback Control, Reference Tracking Feedforward Control, Model-based Torque Control. The proposed control framework is designed taking into consideration of the linearity of each control algorithm, and thus it enables the continuous and smooth switching of assistive control algorithms, and makes it possible to analyze the stability of the overall control loop. The proposed method is implemented into a lower-limb exoskeleton robot and is verified by experimental results.

1. Introduction

Assisting elderly and dependent people by enhancing and strengthening movement of the lower limbs has raised particular attention due to the considerably increasing rate of this population, and exoskeletons are considered as one of the most potential assistive devices for this enhancement. The exoskeletons are recently drawing large attention from the public as well as researchers [1]. Several companies have developed exoskeletons to help paraplegic individuals walk and succeeded in commercializing them [2–5]. Even though those exoskeletons are still limited in their functions and accessibility due to the expense, they can be the most functional mechanical device to support and assist human motions; they provide physical assistive torques for assistance and rehabilitation of the aged people with muscular weaknesses or patients with physical impairments.

The difference of the required control strategy is mostly determined by the level of the muscle force that the wearer can generate, e.g., the level of the required force that the assistive robot should

---

* Corresponding author.
E-mail addresses: sehoon74@sogang.ac.kr (S. Oh), baieunrong@sogang.ac.kr (E. Baek), songsk@sogang.ac.kr (S.-k. Song), samer.mohammed@u-pec.fr (S. Mohammed), dyjeon@sogang.ac.kr (D. Jeon), kckong@sogang.ac.kr (K. Kong).

http://dx.doi.org/10.1016/j.robot.2014.10.001
0921-8890/

provide. In the case of power assistive control, which amplifies the applied human force to achieve a certain task, the users are considered to be able to produce muscle power large enough to cause motions, so that the controllers need to sense the users' force and amplify it. These control processes may be categorized as a kind of impedance control, which changes the interaction force between a human and the assistive robot so that the human does not feel large inertial force when he or she does manipulations through the assistive robot. On the other hand, when the users' ability to generate force is relatively low (e.g., the rehabilitation case), the controller needs to generate the force/position pattern by itself and the users follow it with less muscular forces.

Both control strategies are required for the assistive controller to provide natural and appropriate assistance to humans; the former strategy is considered adequate to the case where arbitrary motion is associated with, e.g., when a human manipulates various stuffs to achieve certain tasks. The latter strategy can be adequate for the case when the motion to be made is relatively small, and large force is necessary, e.g., when a human needs to bear a heavy load with little motion. Humans daily motion such as walking, sitting, and standing consists of the combination of these different cases, and therefore the controller for assistive devices such as exoskeletons is required to be able to conduct both strategies as well as switch the strategies according to the desired motions. In other words, the assistive robots should be able to provide different physical constraints and assistive torques based on the cases the robots are facing [6–8].

A control method that occasionally switches its sub-level control algorithms, or at least controller gains, is called a hybrid control method. The hybrid control scheme has been applied to various assistive robots in recent years. For example, the HAL, a full-body assistive robot developed with multiple purposes, uses the hybrid control method that changes the control algorithms according to the motion phases while walking, where the motion phases are detected by the ground reaction force patterns and are classified by the type of muscular activities (e.g., active, passive, and free modes) [5]. The BLEEX also applies the hybrid control method [9] for assisting walking motions; the controller of the BLEEX has two main sub-control algorithms, where the master–slave control method is activated in a stance phase, and the sensitivity amplification control method is used in a swing phase. The foot pressure patterns are also used in the BLEEX system for detecting the motion phases. Similarly, the LOKOMAT also uses a hybrid control method that alternately switches force-mode control and position-mode control according to motion phases for rehabilitation purposes. The LOKOMAT also divides the walking motion into two phases, the stance and swing phases, which are detected by the knee and hip joint angles. In the force-mode control of the LOKOMAT, an impedance controller is realized in the feedback and feedforward control structure, where the controlled output is the interactive force between the human and the robot. On the other hand, in the position-mode control the impedance of the robotic leg is significantly increased for driving the motion of the wearer [10].

Even though these hybrid control methods have been successfully implemented in various assistive robots and their performance has been proved in practice, there is no research that can give a comprehensive viewpoint and insight including the stability of the switching of this hybrid control for assistive robots. In particular, the stability of assistive robots is very critical, since it is directly related to the safety of the wearer. Therefore, it is very important to prove the stability and performance of the hybrid control method of assistive robots not only in practice, but also from the theoretical point of view. In order to address this problem, this paper attempts to provide general and comprehensive viewpoint of the assistive controllers by proposing a generalized control framework of assistive controllers. The proposed framework incorporates various control algorithms that can be adopted as an assistive controller and provides fundamentals for theoretically and practically analyzing the stability and performance of a hybrid control method.

The paper is organized as follows. Section 2 categorizes control algorithms that are widely utilized for the assistive robots and incorporates them into a framework which can be a generalized control framework for assistive controllers. A motion-phase-based hybrid assistive control for walking is designed based on the proposed framework in Section 3. The stability and robustness of the control framework are analyzed taking into consideration the switching between control algorithms in Section 4. Finally, the proposed algorithm is verified through the experimental results in Section 5.

2. Generalized control framework of assistive controllers

Fig. 1 shows a generalized control framework that can incorporate various assistive control algorithms. The proposed control framework categorizes the general widely utilized control algorithms into Reference Tracking Feedback Control, Reference Tracking Feedforward Control, Feedforward Disturbance Compensation Control, and Model-based Torque Control. The gains, $K_{1,2,\ldots,5}$, are the switching parameters that allow integration of the whole control algorithms and transition from one control scheme to another.

2.1. Feedforward Disturbance Compensation Control

This control is to compensate for the disturbances that can be known or modeled beforehand. In an assistive robot equipped with geared motor systems, the friction and damping are imposed on the human body, which disturb not only the tracking performance of the feedback controller but also the voluntary motion of the wearer. In addition, the gravitational and inertial forces caused by the mass of the robot hardware are another major factor that distracts the human motion.

A simple yet effective friction and gravity compensation (FGC) algorithm which can be given as (1) is the most commonly used controller for Feedforward Disturbance Compensation Control [11–13].

$$u = c_0\,\mathrm{sign}(\dot{\theta}) + c_1\dot{\theta} + c_2\sin(\theta), \tag{1}$$

where c_0, c_1, and c_2 are the constant gains related to the magnitudes of the Coulomb friction, the viscous damping, and the gravitational inertia, respectively.

2.2. Reference Tracking Feedback Control

Reference Tracking Feedback Control can be designed by any feedback control method, such as PID (proportional-integral-derivative), $\mathcal{H}_\infty$, or sliding mode control which feeds back a tracking error between a reference input and a controlled output such that the output tracks the reference. The control does not only guarantee tracking of the pre-determined trajectory, but also changes the impedance of the robots.

PID (Proportional–Integral–Derivative) controller is the most common form of Reference Tracking Feedback Control, which can be also called natural admittance control (NAC) [14] since it affects the impedance (or admittance) of the system.