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# A Generalized Control Framework of Assistive Controllers for Lower Limb Exoskeletons

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***Abstract*— A number of control methodologies have been studied for assistive robotic technologies. Since the human motions in a daily life consist of multiple phases, such as walking, sitting and standing, controllers for assistive robots are required to be able to cope with different motion phases. For this reason, hybrid control which is able to occasionally switch control algorithms according to the motion phases has been preferred in the assistive robots, in particular wearable robots. In this paper, a generalized control framework is proposed as a fundamental framework for the hybrid assistive control and its stability is analyzed using the framework. The proposed control framework is implemented into a lower-limb exoskeleton robot and its effectiveness is verified thorough experiments.**

## I. INTRODUCTION

As the elderly population has increased continuously, the role of assistive robots that physically and autonomously support the elderly in daily lives becomes more and more important due to the lack of young population who are in charge of physical support for the elderly[1]. The assistive robots, including exoskeletal robots, may be a good means for assistance and rehabilitation of the aged people with muscular weaknesses or patients with physical impairments, as they support joint motions with physical assistive joint torques.

As most of the assistive robots are worn by humans, i.e., so-called wearable robots, it is important that joint motions of the robots should be properly synchronized with the human joint motions. For this reason, various intelligent control methods have been investigated as one of the most important technologies in the assistive robot systems[1],[2].

Meanwhile, the human motions in a daily life consist of various characteristic phases, such as walking, sitting, and standing, of which the physical constraints and requirements for assistance are all different. Moreover, the walking motion can be categorized into several sub-phases, such as an initial contact, a mid-stance, a terminal stance, and a swing. It should be noted that the muscular actions are all different according to the motion phases. Therefore, different control schemes should be applied for assisting sit-to-stand and stand-to-sit motions. Likewise, the sub-phases of walking motion also require implementing different control methods. Such characteristics necessitate that control algorithms should be continuously switched according to the motion phases.

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 to reflect human's time-varying muscular characteristics. For example, the HAL used the hybrid control method that changes the control algorithms according to the motion phases while walking, where the motion phases were detected by the ground reaction force patterns and were classified by the type of muscular activities (e.g., active, passive, and free modes)[3]. More recently, lower limb exoskeleton for patients with spinal cord injuries developed at Vanderbilt University[4] is operated by a controller that consists of a set of low-level controllers and high-level controllers. The low-level controllers are supervised by a high-level control structure that deduces user's intent based on the position of the center of the mass projection on the ground plane. The low-level controllers composed with variable proportional-derivate (PD) feedback controllers at each joint. With this control structure, the impedance of each joint could be generated selectively according to the user's intent[1]. As another example, an active orthosis of Rio Grande do Norte University[5] has a command-control system. This active orthosis can assist several motions such as sitting, stopping, and walking and the proper motion to user is generated by electroencephalogram signals, voice recognition or joystick.

Such hybrid control methods have been successfully implemented in various assistive robots and their performance has been proved in practice. However, the aforementioned methods change the gains of a fixed control algorithm structure to generate relatively different assistive forces, instead of converting the control schemes. In addition, although switching the different control algorithms is intuitive and effective, only a few discussions have been made on the stability of the switching. Since stability is directly related to the safety of a wearer, it is very important to prove stability and performance of the hybrid control method of assistive robots not only in practice, but also in the theoretical point of view. In order to address this problem, this paper proposes a generalized control framework that provides fundamentals for theoretically and practically analyzing the stability and performance of the hybrid control method that incorporates different assistive control algorithms. Since the proposed control framework can emulate the transition between control algorithms by a sole parameter in the same controller structure, the stability of the transition can be analyzed using

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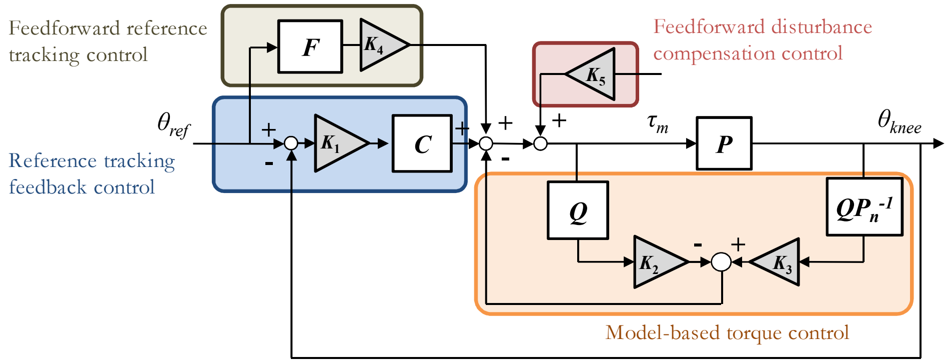


Fig. 1. A generalized control framework that incorporates various assistive control algorithms.

linear system theory.

## II. Generalized Control Framework for Assistive Controllers

### A. Configuration of the Proposed Control Framework

An assistive controller in the proposed framework is able to realize reference tracking feedback control, reference tracking feedforward control, feedforward disturbance compensation control, and model-based torque control. Reference tracking feedback control and reference tracking feedforward control are related to the performance of reference tracking and can be designed using various conventional control methodologies which have been utilized for industrial robots.

The feedforward disturbance compensation control and the model-based torque control are to response to exogenous forces; the gravity and friction force can be compensated by the feedforward disturbance compensation controller, and the impedance against the exogenous force can be directly modulated by the model-based torque controller.

In this paper, following four control algorithms are designed and applied to constitute the hybrid control for a lower limb exoskeleton.

*1) Natural Admittance Control, NAC:* When a pre-defined trajectory is available, a position feedback controller is often applied for the human joint to follow the trajectory. Such a control method is called natural admittance control(NAC)[6], and this NAC can be utilized as the reference tracking feedback controller. In this paper, a proportional-derivative(PD) controller, i.e., $u = k_p(\theta_d - \theta) + k_d(\dot{\theta}_d - \dot{\theta})$, is designed as the reference tracking feedback control. Notice that this PD control imposes virtual damping and stiffness between the robot and a human.

*2) Disturbance Observer, DOB:* The disturbance observer(DOB)[7] rejects a lumped disturbance including exogenous forces. DOB can be categorized as the model-based torque control since it directly controls the inertial torque which generates acceleration. The rejection of exogenous forces results in high impedance against the external force.

*3) Impedance Reduction Control, IRC:* In the same way as DOB, the impedance reduction control(IRC) controls a response of the system against the exogenous force. Unlike DOB, IRC is designed to make the system compliant against the exogenous forces and thus to reduce the impedance. In this paper, IRC is designed to reduce an inherent mechanical impedance of a wearable robot.

*4) Feedforward Control, FF:* Feedforward(FF) control is applied as the reference tracking feedforward control to compensate for the time delay which comes from gear chains in a wearable robot. The FF control method also enables providing the actuation (i.e., assistive) force even prior to the human motion avoiding the causality problem of feedback control methods.

*5) Friction and Gravity Compensation, FGC:* The feedforward disturbance compensation control can be utilized to remove any disturbance that can be known beforehand. In this paper, a controller to compensate for friction and gravity, which is named friction and gravity compensation(FGC), is designed based on the Coulomb friction model, i.e., $f_\mu = -k_0 \mathrm{sign}(\dot{\theta})$ (where $\theta$ is the relative angle of the associated joint) and the nominal value of the body-segment weight.

### B. Realization of Various Impedance in the Proposed Control Framework

The proposed control framework in Fig. 1 includes all the assistive controllers explained above and switches the controllers by change the gains, $K_{1,2,\ldots,5}$. Among the assistive control algorithms, the reference tracking feedback control and the model-based torque control are related to the impedance of the system against the exogenous force. For this reason, the gains, $K_1, K_2$ and $K_3$, determine the impedance realized in the proposed control framework; when $K_2$ is set to 0, and $K_3$ is set to $-q$, the proposed method realizes IRC. When both $K_2$ and $K_3$ are set to 1, the blocks labeled “Model-based Torque Control” becomes DOB. In the same way, $K_1$ determines the impedance generated by the feedback controller $C$. In other words, variable values of $K_1, K_2$ and $K_3$ realize the variable impedance in the proposed method.

In addition to the realization of variable impedance characteristics, the switching gains also enable the analysis of stability during switching, which will be explained in the following section.

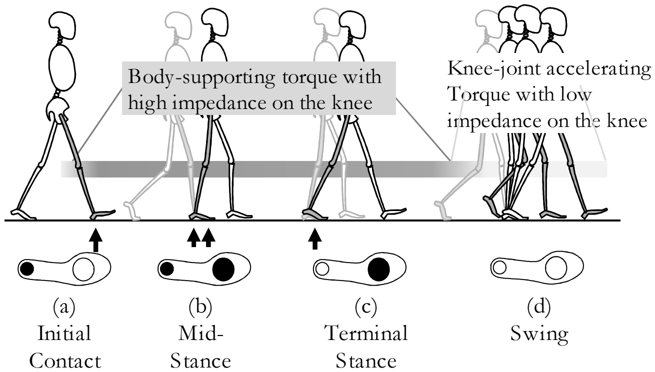


Fig. 2. The characteristics of the required assistive torque during walking

TABLE I

APPROPRIATE FEEDBACK CONTROL ALGORITHMS

| Motion phase | Control Algorithms |
|---|---|
| Initial Contact | NAC(reference tracking feedback control) |
| | DOB(model-based torque control) |
| Mid-Stance | NAC(reference tracking feedback control) |
| | DOB(model-based torque control) |
| Terminal Stance | NAC(reference tracking feedback control) |
| Swing | IRC(model-based torque control) |

TABLE II

APPROPRIATE CONTROL ALGORITHMS FOR EACH MOTION PHASE

| Motion phase | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ |
|---|---|---|---|---|---|
| Walking (Initial Contact) | 1 | 1 | 1 | 1 | 1 |
| Walking (Mid-Stance) | 1 | 1 | 1 | 1 | 1 |
| Walking (Terminal Stance) | 0 | 0 | 0 | 0 | 1 |
| Walking (Swing) | 0 | 0 | $-q$ | 0 | 1 |

## III. MOTION-PHASE-BASED WALKING ASSISTIVE CONTROL UTILIZING THE GENERALIZED CONTROL FRAMEWORK

In this paper, a hybrid controller to assist walking motions is designed utilizing the proposed control framework. Notice that strategies proposed in this paper are not restricted to walking motion but can be extended to the other motions which consist of various motion phases.

### *A. Motion Phase Detection Algorithm*

The walking motion involves stance and swing which can be easily recognized by comparing the ground reaction force(GRF) of each foot. In this paper, the walking motion is divided into four functional patterns developed in [8], which is illustrated in Fig. 2. Characteristics of the gait phases and methodology to detect them are as follows.

*1) Phase 1: Initial Contact:* During this phase, the leg in Fig. 2 starts contacting the ground, and the GRF appears only at the heel as shown in the bottom of Fig. 2(a).

*2) Phase 2: Mid-Stance:* When both the forefoot and heel start contacting the ground, as shown in Fig. 2(b), the Mid-Stance phase starts.

*3) Phase 3: Terminal Stance:* As the center of body mass moves forward in the Terminal Stance phase, the heel starts taking off, as shown in Fig. 2(c). In this phase, only the forefoot part touches the ground.

*4) Phase 4: Swing:* The foot does not touch the ground so that there is no GRF measured by sensors.

A motion phase detection algorithm(MPDA) designed in [8] based on the characteristics explained above is employed in this paper to determine current motion phases, and pressure sensors are utilized to measure the GRFs. The MPDA calculates the likelihood of each motion phase (i.e., $\mu_{1,2,3,4}$) according to the pressure sensor measurement and a fuzzy logic algorithm[8].

### *B. Design of Hybrid Assistive Controller in the Proposed Control Framework*

The knee joint torque during walking has different characteristics according to the motion phases: supporting of the body weight and acceleration of the shank and foot. These different characteristics can be analyzed in terms of the impedance; the high impedance is required in a stance phase, and the low impedance is necessary during a swing phase.

This variable impedance characteristic can be realized by changing the switching gains of the reference tracking feedback controller and the model-based torque controller of the proposed framework as Table I. The switching of these control algorithms needs to occur according to changes of motion phases and should be continuous to prevent uncomfortable feeling. In order to address this problem, the switching gains, $K_{1,2,...,5}$ in Fig. 1, are determined as functions of the likelihoods of the motion phases, i.e., $\mu_{1,2,3,4}$ as follows.

$$K_1 = \mu_1 + \mu_2 \tag{1}$$
$$K_2 = \mu_1 + \mu_2 \tag{2}$$
$$K_3 = \mu_1 + \mu_2 - q\mu_4 \tag{3}$$
$$K_4 = \mu_1 + \mu_2 \tag{4}$$

$K_5$ is set to 1 regardless of the phases, since the FGC is required for all the phases during walking. Consequently, the switching gains to constitute the proposed hybrid assistive control framework are set as in Table II.

### *C. Stability Analysis of the Proposed Hybrid Control Algorithm*

The changing of poles of the proposed system according to the time-varying switching gains is observed to analyze stability. If the poles during switching are all in the left-half plane, the system is stable regardless of the time-varying gains with necessary assumptions.

Since the feedback stability is a main concern, the parameters $K_1, K_2$ and $K_3$ which are involved in the feedback loop are to be analyzed. For the sake of simplicity, these three parameters can be replaced with only one gain with different scalings. The following equations show how $K_1, K_2$ and $K_3$

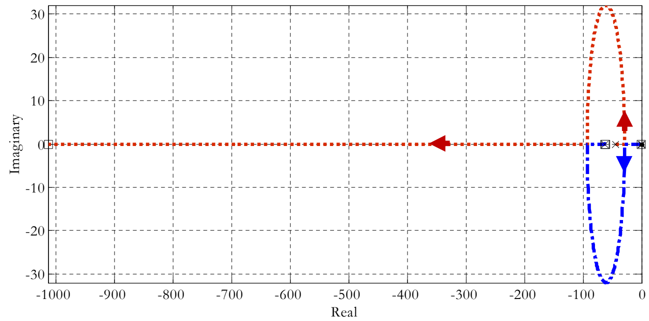


Fig. 3. Root locus with the change of $K$. The roots start from the square to the x mark by changing the parameter $K$ from $-1$ to 1

are replaced with a new variable, $K \in \mathbb{R}^1$, $|K| \leq 1$:

$$K_1 = \left(K\frac{1}{2} + \frac{1}{2}\right) \tag{5}$$

$$K_2 = \left(K\frac{1}{2} + \frac{1}{2}\right) \tag{6}$$

$$K_3 = \left(K\frac{1+q}{2} + \frac{1-q}{2}\right), \tag{7}$$

This $K$ can cover the variance of both $K_1$ and $K_2$ that range from 0 to 1 and the variance of $K_3$ that is from $-q$ to 1.

The location of poles with respect to the variance of $K$ is examined and shown in Fig. 3, where the plant model was a simplified and linealized model of the human body wearing an assistive robot, $Q$ filter of DOB and IRC was set to $\frac{1}{1/(2\pi\cdot 10)s+1}$, and the feedback controller $C$ was set to a proportional-integral (PI) controller with the P gain of 10 and the I gain of 1, which were determined based on trials and errors.

All the poles are on the left-half plane regardless of the value of $K$, which shows that the proposed hybrid assistive control is stable when the rate of $K$ is acceptably slow. There are four poles in the system, two of which are from the integral control and the $Q$ filter, which are located on $\frac{1}{\tau}$ (62.83 in this case) and 0. The location of these two poles does not move significantly in Fig. 3.

The remaining two poles are from the plant with the feedback of the inverse model. The transition of these two poles appears mainly in Fig. 3. These poles shift farther from the origin as $K$ increased from 0 to 1, which means the impedance becomes larger when $K$ becomes close to 1. This result validates that the proposed hybrid assistive control changes the impedance of system in a stable way.

## IV. Experimental Verification

### A. System Configuration: A Knee Joint Assistive Robot

A knee joint assistive robot in Fig 4 was used for an experiment. The robot consists of Compact Series Elastic Actuator(cRSEA) modules which realize the torque-mode assistive control with zero impedance on the joints. Even though the robot is a full lower-extremity assistive robot with four cRSEA installed on the hip and knee joints, only the knee joints were utilized in this experiments. The specification in details can be referred to [9].


Fig. 4. Assistive robot with cRSEA[9]

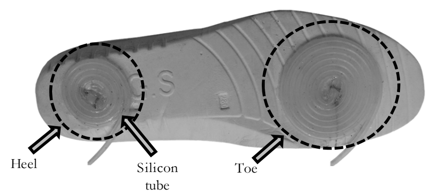


Fig. 5. Smart shoe to measure GRF

The GRF was measured using the smart shoes which have silicone tubes rolled at the toe and the heel as in Fig 5. The air-pressures at the toe and heel were measured and processed through the MPDA algorithm proposed in [8] to detect the gait phase.

### B. Hybrid Assistive Control for Assisting Walking

Figure 6 is the experimental results where a subject wearing the assistive robot walked two steps with the control algorithm developed in Sec. III.

A reference knee joint angle given in (8) was calculated based on a trajectory generation algorithm using the knee joint angle pattern of healthy people. Using the period $T_{pr}$ obtained from the previous step, (8) can generate a real-time reference angle for the knee joint, $\theta_{ref}(t)$.

$$\begin{aligned}\theta_{ref}(t) &= 20.19 + 18.15\cos(\frac{t}{T_{pr}} + 1.72) \\ &+ 14.49\cos(\frac{2t}{T_{pr}} - 2.46) + 4.9\cos(\frac{3t}{T_{pr}} - 1.54)\end{aligned} \tag{8}$$

Figure 6(a) shows the reference angle and the measured angle. Since the assistive control does not require high precision, errors in the angle are acceptable for assistive control.

The phases of the walking were detected as in Fig. 6(d), and the switching gains $K_2$ and $K_3$ also were determined as in Fig. 6(e) based on (2) and (3). Fig. 6(c) is an output of model-based torque controller which is switched by these $K_2$ and $K_3$, which shows that the switching by the proposed algorithm could continuously switch the model-based torque control between DOB and IRC, and thus change the impedance; the model-reference tracking control could generate resistive torque to support the body weight during Mid-Stance phase (from 2.5 to 3.5 seconds and from 8 to

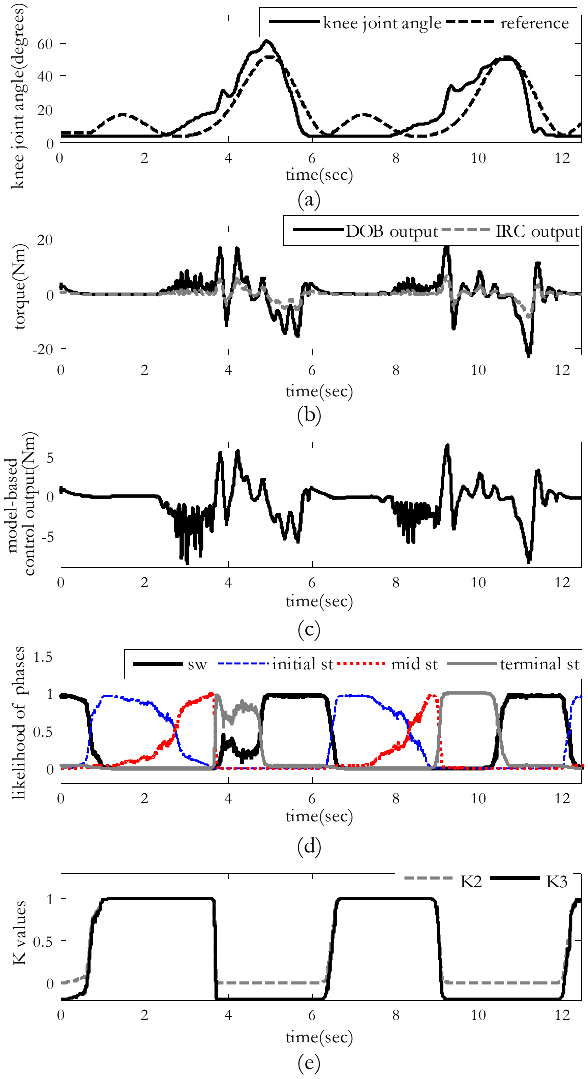


Fig. 6. Assistive control experimental result ((a) knee joint angle (reference and measurement), (b) output of DOB and IRC, (c) the output of the model-based torque control, (d) likelihood of phases, (e) weighting parameters)

9 seconds), which is presented by the negative torque. The negative torque is in the direction to extend the knee joint while the knee joint was flexing. On the other hand, the model-based torque control provided a positive torque during the swing phase which is in the same direction with the external force (which can be estimated from the output of DOB in Fig. 6(b)) so that it accelerated the flexion of the knee joint.

By this experiment, it is shown that the proposed control framework could provide continuous and safe switching impedance that is required for the assistance of walking.

## V. Conclusion

This paper presented a generalized control framework for hybrid assistive control. The various control algorithms that can be utilized in assistive control were resolved in the proposed method and realized by adjusting a few gains in this paper, which allowed continuous and intuitive switching of control algorithms.

The proposed control method was applied to a lower limb exoskeleton during the walking motion, and the adjusting gains were designed as functions of the detected motion phases. The performance of the proposed control was verified by experiments and the result showed that the proposed control framework could successfully adjust impedance to support various motion phases.

The application of the proposed control framework will not be limited to wearable robots, but also be extended to any human-interactive systems.

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