# 보우덴 케이블 동력 전달 방식에서 적응형 백래시 제어

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# Adaptive Backlash Control in Bowden Cable Transmission System

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*Key Words : Bowden Cable( 케이블), Adaptive Control(적응형 제어), Backlash Model(백래시 모델)*

## ABSTRACT

Bowden cable transmission is one way to transmit power. It is compliance that end-effector can move freely in space. Compared to nominal transmission such as gears and belts, it has low efficiency due to its nature. The friction based transmission contains side effects(dead-zone, hysteresis, backlash). In this paper, we model the system as backlash and compensate the bowden cable characteristic with adaptive inverse backlash model. We simulate the controller and implement it to verify the performance. Reference tracking performance is improved with RMSE and peak error reduced.

## 1. Introduction

Bowden cable transmission is widely used in human−interaction problem or distant transmission. The well−known application is bicycle brakes. Also, surgical robots such as endoscopic tools use this transmission due to its compactness and far transmission capability. Bowden cable transmission has own advantage different from nominal transmission such as gears and belts. It is flexible that end−effector can move freely through space. However, it transmits power based on static friction between sheath and cable. It causes side effects (hysteresis, backlash and dead−zone). The main factor that influence the system is cumulative bending angle[1]. To overcome this characteristic, various studies have been done. Do, T.N.,et al model the system as ‘asymmetric backlash−like hysteresis model’ and use feed forward compensator to control position[2]. Dinh, Binh Khanh, et al. use ‘normalized Bouc−wen model’[3]. In normalized Bouc−wen model, there are six parameters to estimate. they use adaptive control to converge the error even though the configuration(cumulative bending angle) varies. Useok Jeong and his team use loop routing to make all configuration close to 360 deg bending angle[4]. Also, using tension sensor to observe the situation and it compensates its nature using feedforward controller.

In this paper, we model the system characteristic as backlash and compensate backlash to control position using adaptive inverse backlash control scheme. In section 2, simple backlash model is introduced. This model is widely used in aircraft and signal that contains backlash. In section 3, we illustrate control algorithm called adaptive inverse backlash. In section 4, we show experiment results and analysis. Finally in section 5, conclusion is introduced.

## 2. System Model

### 2.1. Simple Backlash Model

In this section, we introduce general backlash model[5]. It has 3 parameters(m, $c_r$, $c_l$) to illustrate backlash situations. m represents how input and output are related. To be specific, when input moves as output moves, if m =1 means that input and output move in same ratio like 1 ratio gear train. $c_r$ and $c_l$ mean cross−point with x axis

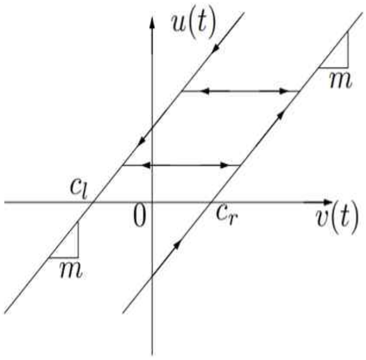



Fig. 1 Backlash Model

and lane(r : right, l: left). Eqn (1) shows three cases at which backlash situation. First, if input(v(t)) increases and it is in right line, output follows input with delay. Also, if input decreases and it is in left line, output decreases as input decreases. backlash occurs when no upper situations(see Fig. 1). backlash means that when

$$u(t) = \begin{cases} m\dot{v}(t) & \text{if } \dot{v}(t) > 0 \text{ and } u(t) = m(v(t) - c\ ) \\ m\dot{v}(t) & \text{if } \dot{v}(t) < 0 \text{ and } u(t) = m(v(t) - c_l) \\ 0 & otherwise \end{cases} \qquad (1)$$

input's velocity sign is switched, output stays same position even though input moves.

## 2.1. Discrete-time Representation

In most applications, digital controller are used which means that input signal is piecewise constant. Eqn (1) is no longer available because it is hard to detect the sign switching point and backlash point(output stays constant). For such discrete-time application, we have to modify the Eqn (1) to be implemented. Eqn (2) is modified equation of Eqn (1).

$$u(k) = \begin{cases} m(v(k) - c_l) & for\ v(k) < v_l \\ m(v(k) - c_r) & for\ v(k) > v_r \\ u(k-1) & otherwise \end{cases} \qquad (2)$$

where $v_l = \frac{u(k-1)}{m} + c_l$ , $v_r = \frac{u(k-1)}{m} + c_r$

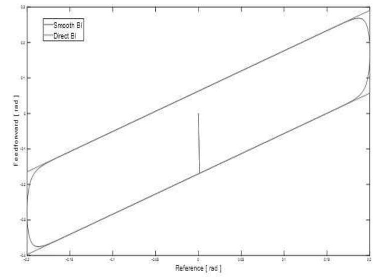


Fig. 2 Inverse backlash (smooth vs Direct)

# 3. Control Algorithm

## 3.1. Adaptive Inverse Backlash

### 3.1.1. Smooth Inverse Backlash

backlash is significant in electrical or mechanical system. backlash causes two main side effects. During system proceeds, data loss occurs. Also, when with backlash, it is hard to track the input or reference. In summary, backlash makes it hard to sense and actuate in both situation. In case of bowden cable system, Both problem happen in terms of haptic feedback information loss and lack of tracking desired torque or position. Inverse backlash will reduce or eliminate this side effects modifying signal.

In theoretical concept, direct inverse backlash makes sense that it eliminate its undesirable effect. However, in practical point of view, non-differentiable controller like direct inverse backlash makes system unstable. we use smooth inverse backlash using error function at switching point as we describes in Eqn (1). As a result, feedforward backlash compensator is differentiable with one simple equation(Eqn (3)) (see Fig. 2)

$$\theta_F = \frac{\theta_{ref}}{m} + c_r\ {}_r + c_l X_l \qquad (3)$$

where, $X_r = \frac{1 - erf(k\dot{\theta}_{ref})}{2}$ , $X_l = 1 - X_r$

### 3.1.2. Adaptive Law

In real world application, bowden cable changes its configuration during human-interaction. It means that as we model the system as backlash, backlash's three parameters varies. To overcome this situation, we use adaptive law to converge tracking error to zero and estimates the parameters. In this paper, we are not going to illustrate the proof of adaptive law that it converges using Lyapunov function. Adaptive scheme that we use well explains in previous literature[5].

$$(k+1) = \Theta(k) - \frac{\gamma\omega(k-1)e(k)}{1+\omega \ \omega} - \sigma(k)\Theta(k) \qquad (4)$$

where, $\Theta(k) = \ mc \ \ m \ \ mc_l]_k^T$, $\omega(k-1) = \ \ _r \, v(k-1) \, X_l]^T$

, $0<\gamma<1$, $\sigma(k) = \begin{matrix} \sigma_0 & \text{if} \ \ \Theta(k)|>2\Theta^* \\ 0 & otherwise \end{matrix}$, $0<\sigma_0<\frac{1}{2}(1-\gamma)$

Eqn (4) is based on gradient algorithm. $\Theta(k)$ means that 3 parameters are estimated every time segment and updated. $v(k-1)$ is prior feedforward motor input. $X_r$ and $X_l$ are calculated based on reference velocity and controller parameter $k$ (see Eqn (3)). In constraint of $\sigma(k)$, it is based on true parameters. For real implementation we find available value that makes the system converges.

To sum up, $\sigma_0$, $\Theta^*$, $k$ and $\gamma$ are controller parameters that we have to decide that makes system converges based on Eqn (4)'s constraints.

### 3.2. Control Block Diagram

During upper sections, we discuss backlash model and its smooth inverse. Also, to implement the controller we highlight adaptive law. In this section, we summarize previous section and illustrate whole control architecture.

In Fig. 3, reference position at $k^{th}$ time segment is going through 'backlash compensator'. In this part, we use Eqn (3) to compensate backlash while bowden cable stays even if motor moves. Feedforward position is modified signal of the reference that eliminates backlash effect.

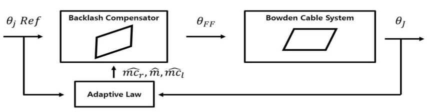



Fig. 3 Block diagram of adaptive Inverse backlash control

In bowden cable system, joint moves as motor moves. However, as we discuss before, bowden cable has its own characteristic that does not transmit accurate position like gears and belts. Therefore feedforward motor input moves more than reference position to make joint follow the reference.

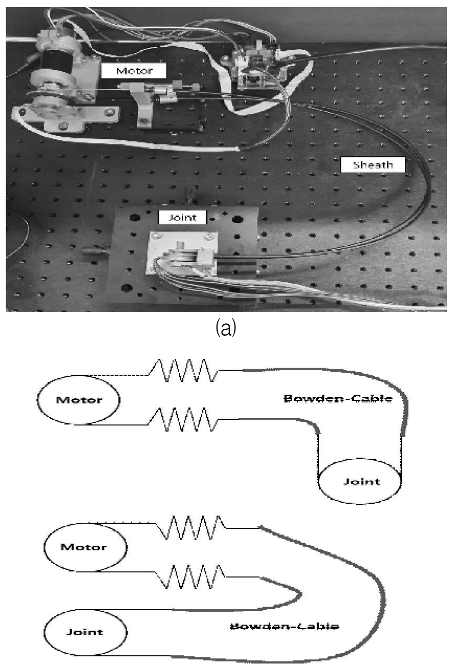
Finally, in adaptive law, we observe the three parameters($\Theta(k)$) using joint encoder and motor encoder. From this information, we use Eqn (4) to estimate the parameters and make error converge to zero.

## 4. Result

### 4.1. Experiment set up

Hardware configuration consists of motor, cable and joint. Motor with driver follows feedforward signal calculate from computer with real-time operating system. As motor rotates, joint rotates with bowden cable characteristic. Computer computes the adaptive law from reference, joint and motor position information.

Experiment has been done with following setting(see Fig. 4). we compared 3 experiments. $1^{st}$ and $2^{nd}$ configuration are each 90 deg and 180 deg bending angle. results is from each configuration without control and




(a)

(b)

Fig 4 (a) Experiment set up and (b) Two configuration ( upper : $1^{st}$ and down : $2^{nd}$ )

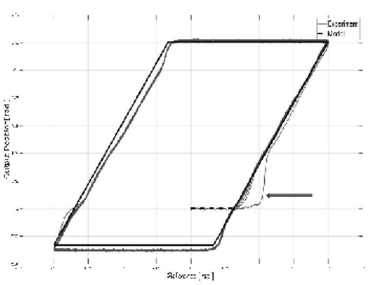
moving joint with adaptive inverse backlash control. we check adaptiveness with changing configuration from experiment result.

### 4.2. Model vs Experiment

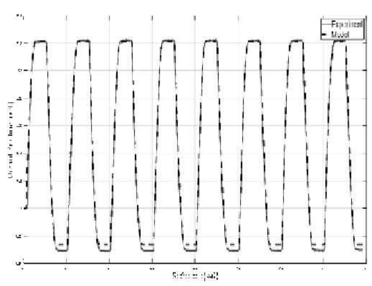
In this section, we shows how similar bowden characteristic and backlash model are. we use sine wave with 0.2 rad amplitude and 0.5 Hz frequency. This signal rotates motor and output is joint position. In Fig.5, model almost approximates the system nature without start point. At start position, cables does not have enough tension to transmit power. Also, we conclude that due to its simplicity in the model. It is hard to fit the model to bowden cable system that contains inner non−linearity.

### 4.3. Tracking performance

As we illustrate in section 4.1, we compare three experiment setting that is two configurations without control and varying configuration with adaptive control. Reference signal is same as upper condition(0.2 rad amp, 0.5 Hz freq sine wave).

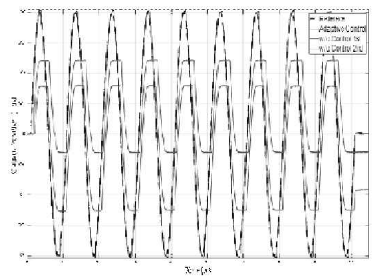


(a)

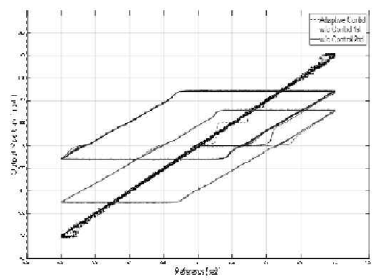


(b)

Fig 5 Compare backlash model and bowden characteristic (a) Input vs output (b) Time series output
(dashed : model, solid : experiment)



(a)



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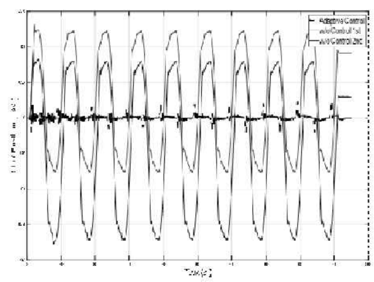
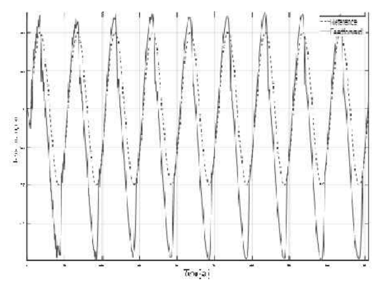


(c)



(d)

Fig 6 Compare with adaptive control and without control (a) time series output (b) reference vs output (c) time series error (d) feedforward signal and reference

In Fig. 6 (a), varying configuration impacts system performance without control. In 1$^{st}$ configuration, it does not track reference signal. Also, if bending angle of cable increases, tracking capability decreases. when with human−interaction, configuration changes gradually.

Therefore it causes discomfort without control. However with adaptive control, we compensate backlash and adapt the parameters to compensate varying configuration. In Fig. 6 (b),(c), it shows that even though the configuration changes due to human interaction, it compensates undesirable effect. Furthermore, with adaptive control, it is more like gears and belts with flexibility. Table 1 shows that how much tracking capability increases with this method. However, as Fig 6 (d) shows, motor has to rotates more compare to reference signal to compensate backlash.

Table 1 Error Analysis

| | Adaptive Control | Without Control |
|---|---|---|
| RMSE | 1.8e-05 rad | 0.011 rad |
| Peak error | 0.0235 rad | 0.180 rad |

## 5. Conclusion

This paper shows one way to compensate bowden cable backlash. we use general backlash model that used in various field such as signal processing[6] and aircraft control[7]. From this model, instead of using direct inverse form of backlash equation, we proposed differentiable feedforward equation with error function. It makes switching point of backlash smooth. Moreover, adaptive law shows adaptiveness that during changing configurations it cancel the effect that has different dynamics. There need more research to be done that we do not explain frequency domain analysis and real- world application. These are needed to further research.

From this result, we conclude that this method can be used various field such as surgical robot or wearable robot. Expecially, in wearable exo-hand, rotary series elastic actuator(RSEA) make design compact and with this technique we sure that it can be used during rehabilitation and haptic interface.

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