EXPERIMENTAL STUDIES OF IMPEDANCE FORCE TRACKING CONTROL OF A CRACK SEALING ROBOT FOR HIGHWAY MAINTENANCE*

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Abstract: This paper presents experimental studies of impedance force tracking control algorithm for a crack sealing robot. The robot is built to find and seal cracks on the pavement. Regulating contact force improves the performance of cleaning process before sealing. The proposed impedance force control method is robust to perform tasks under unknown surface condition such as stiffness and position of the environment. Experimental studies show that the robot regulates a desired force quite well on the curved unknown environment.

Keywords: Crack sealing robot, impedance force control, highway maintenance.

1. INTRODUCTION

Nowadays, highway maintenance technology is required to provide a stable traffic flow preventing any accident on the highway. One of maintenance technologies is to keep road surface condition clean. Unstable condition of road surface can cause uncomfortable driving, even deadly accidents.

Recently, researches on technologies of highway maintenance have been actively developed at AHMCT(Advanced Highway Maintenance and Construction Technology) center in UC Davis. Among many projects, they have built a crack sealing automobile that seals cracks on the highway (Lasky *et. al*., 2000). The process of a crack sealing robot can be divided into three parts : detecting, cleaning, and sealing crack. The corresponding hardware parts are sensing, processing, and control. The sensing part uses camera and laser sensors to detect crack. Images of detected crack are analysed to obtain the location of the

*This research has been supported by KRF-2002-002-D00076 of the Korea Research Foundation in Korea. The authors would like to thank the KRF for their generous financial support.

crack. Then the control part cleans up crack and seal it. A whole system appears to be massive and bulky. To obtain better results, force control is used to regulate the contact force on the ground. Force control is known as a sophisticated control method that has to control the force as well as the position of the robot. The hybrid force control and the impedance force control are two main streams of a control concept (Raibert *et. al* , 1981 and Hogan *et. al*., 1985). Based on these two control strategies, various modified force control algorithms have been proposed (Anderson *et. al*, 1987 , Liu *et. al*. 1991 , Seraji *et. al*, 1994, Jung *et. al*, 1999). The force tracking impedance control algorithm that can specify a desired force directly, and perform force tracking under unknown environment has been proposed (Jung *et. al*., 1999 and Jung *et. al*., 2000). A fuzzy force control method to deal with unknown environment has been proposed (Kiguchi *et. al*., 2000) as well as the neural force control algorithm that can compensate for all the uncertainties under unknown environment by using neural network (Jung *et. al*. 1998).

In this paper, an autonomous crack sealing robot is developed. Before sealing crack, the crack sealing robot finds crack by using a laser sensor and a vision sensor, determines the location, and tracks the crack on the pavement while contact force on the ground is regulated. Performances of the force tracking impedance control algorithm are tested experimentally. To test the robust performance of the proposed force control algorithm, environment is designed as a curved shape to give an arbitrary unknown location to the robot. And at the same time, two different materials of the environment are used to test the robustness of the control algorithm for unknown stiffness. The sealing robot is required to maintain a desired force by following the trajectory of the curved wood and the curved steel environment. Experimental results show that the proposed controller is very robust under unknown environment uncertainties. Performances of the impedance force tracking control are very good and stable under unknown environment.

2. IMPEDANCE FORCE CONTROL

Impedance control method regulates force by selecting impedance parameters correctly. Even though it has lack of a force tracking capability, the dynamic relationship between the robot and the environment is considered. Here, the adaptive impedance force control algorithm is revisited (Jung *et. al*, 1999).

The original impedance closed loop function is given as

$$m\ddot{e} + b\dot{e} + ke = f_e \qquad (1)$$

where $e = x_r - x$ and x_r is the reference location, x is the actual location, and f_e is the external force. m, b, k are impedance gains. By setting appropriate gains, a desired force can be achieved.

In order to give the force tracking capability to (1), inserting the following reference trajectories into (1)

$$x_r = x_e + \Delta x_r \,,\ \Delta x_r = \frac{f_d}{k_{eff}} \qquad (2)$$

yields the nonlinear force tracking impedance function as

$$f_e = m\ddot{\varepsilon} + b\dot{\varepsilon} + k\varepsilon(1 - \frac{f_d}{f_e}) + f_d \qquad (3)$$

where $\varepsilon = x_e - x$, x_e is the environment location and f_d is the desired force.

However, the environment location is measured with uncertainties, the steady state forces can be either $f_e = k\varepsilon'$ or $f_e = f_d$.

To have one correct solution $f_e = f_d$, equation (3) can be formed differently by setting the stiffness gain $k = 0$ such that

$$f_e - f_d = m\ddot{\varepsilon} + b\dot{\varepsilon} \qquad (4)$$

Without knowing the exact stiffness k_e , $f_e = f_d$ is assured at the steady state.

Since the external force can be modelled as the spring system $f_e = -k_e\varepsilon$, substituting it into equation (4) becomes

$$-f_d = m\ddot{\varepsilon} + b\dot{\varepsilon} + k_e\varepsilon \qquad (5)$$

where k_e is the environment stiffness.

In order for the robot to have the over-damped force response, m and b gains are selected as approximated values by the relation

$$b > 2\sqrt{mk_e} \qquad (6)$$

If the environment x_e is not accurately available, in general, it is true for most of cases, $f_e = f_d$ cannot be guaranteed.

Let x_e' include uncertainty in x_e so that $\delta x_e = x_e' - x_e$. Define $\varepsilon' = \varepsilon + \delta x_e$ and replacing ε with ε' at (4) yields

$$m\ddot{\varepsilon}' + b\dot{\varepsilon}' = f_e - f_d \qquad (7)$$

δx_e can be minimized to a certain accuracy by the user. δx_e should be specified inside the environment enough such that $\delta x_e > 0$.

If x_e is constant, then $\dot{x}_e' = \ddot{x}_e' = 0$. Equation (7) becomes

$$m\ddot{x} + b\dot{x} = f_e - f_d \qquad (8)$$

Therefore, at the steady state, $f_e = f_d$ can be obtained.

However, in case that f_d and x_e are time varying, there will be a force tracking error. The force has the error term as $-m\ddot{x} - b\dot{x}$ in tracking a desired force.

In order to make $f_e = f_d$ at (8), the simple adaptive method is proposed as below. Equation (7) can be reformulated as

$$m\ddot{\varepsilon}' + b(\dot{\varepsilon}' + w) = f_e - f_d \qquad (9)$$

where

$$w(t) = w(t-h) + \eta \frac{f_d(t-h) - f_e(t-h)}{b} \quad \eta > 0 \qquad (10)$$

η is an adaptive gain and h is the sampling time. From the spring model of the external force

$$x = x_e + \frac{f_e}{k_e},\ \dot{x} = \dot{x}_e + \frac{\dot{f}_e}{k_e},\ \ddot{x} = \ddot{x}_e + \frac{\ddot{f}_e}{k_e} \qquad (11)$$

Substituting (11) into (9) yields

$$\begin{aligned} & m(\ddot{f}_d - \ddot{f}_e) + b(\dot{f}_d - \dot{f}_e) + bk_e w(t-h) + k_e(f_d - f_e) \\ & = m(\ddot{f}_d - k_e\delta\ddot{x}_e) + b(\dot{f}_d - k_e\delta\dot{x}_e) - \eta k_e(f_d(t-h) - f_e(t-h)) \end{aligned} \qquad (12)$$

By defining $\varepsilon_f = f_d - f_e$ and $\bar{\varepsilon}_f = f_d - \bar{f}_e$, equation (12) becomes

$$\begin{aligned} & m\ddot{\varepsilon}_f + b\dot{\varepsilon}_f + k_e\varepsilon_f + \eta k_e(\varepsilon_f(t-(k-1)h) + \cdots + \varepsilon_f(t-h)) \\ & = m\ddot{\bar{\varepsilon}}_f + b\dot{\bar{\varepsilon}}_f \end{aligned} \qquad (13)$$

\Taking the Laplace transform of the characteristic equation becomes

$$ms^2 + bs + k_e + k_e\eta(e^{-(k-1)hs} + \cdots + e^{-hs}) = 0 \qquad (14)$$

Applying the Taylor series expansion $e^{-hs} \approx 1 - hs$ to (14) yields

$$ms^2 + bs + k_e + k_e\eta\left(\frac{e^{-hs}}{1 - e^{-hs}}\right) = 0 \qquad (15)$$

Applying the Routh-Hurwitz stability criteria to (15), the stable condition of an adaptive gain is found as

$$0 < \eta < \frac{bh}{bh + m} \qquad (16)$$

More detailed stability analysis of this algorithm can be found in the paper (Jung *et. al.*, 1999).

Based on the adaptive impedance force control algorithm, a block diagram is shown in Figure 1. The z axis of the gantry typed robot is force controlled, and x and y directions are position controlled. Sine the z axis is actuated by a ball screw driven by a DC motor, the robot dynamics can be considered as a simple linear system. So the control law becomes very simple.

$$\tau = \frac{1}{m}[b(\dot{\varepsilon}' + w) + f_d - f_e] \qquad (17)$$

Figure 1 shows the control block diagram.

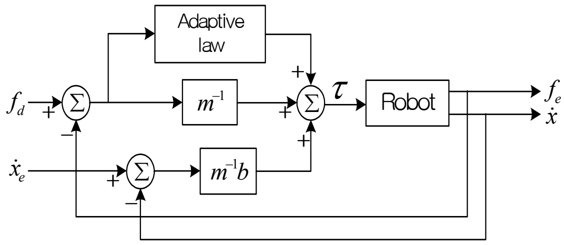

Fig 1. Proposed impedance control

3. CRAK SEALING ROBOT

The developed overall crack sealing robot structure is shown in Figure 2.

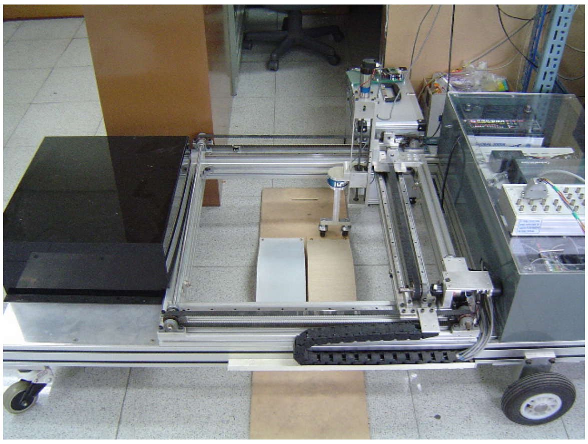

Fig. 2 Overall system structure

The robot is a kind of a mobile manipulator that is a wheeled drive robot with a gantry-typed robot in the middle. The robot consists of three parts: a crack detecting part, a crack sealing part, and an actuator part. The crack detecting part shown as a black box in Figure 2 has a laser sensor and a camera sensor to detect cracks.

The position of the detected crack can be mapped to the robot coordinate to drive wheels. The robot is required to make the crack position be located in the middle of the robot wheels. In this way, the robot tracks the crack. The crack sealing part moves in xyz directions. The force sensor is attached to the z axis so that the normal force to the ground is regulated. The brushing device will also be equipped at the end of the z axis in the near future. In order to minimize the friction forces, two rollers are distantly located apart each other because the crack will be located between two rollers. The actuation part has batteries, computers, actuating motors, and other necessary devices.

4. EXPERIMENT

4.1. Experimental setups

Experimental setup of force control is shown in Figure 3. Environment is made of wood and steel to have unknown different stiffness, and has the round shape to give unknown location. Since the z axis is actuated by a ball screw driven by a dc motor, the gravity force is compensated.

Considering one axis control, Coriolis and centrifugal force can also be neglected. Sine the robot is likely linear the dynamic compensation for a modelling error is not considered.

The robot does not have any knowledge about the environment. The robot is required to track the environment with a regulated force. The JR3 force sensor is used to detect force. Only the normal force to the ground is regulated as shown in Figure 3. The sampling time is 10ms.

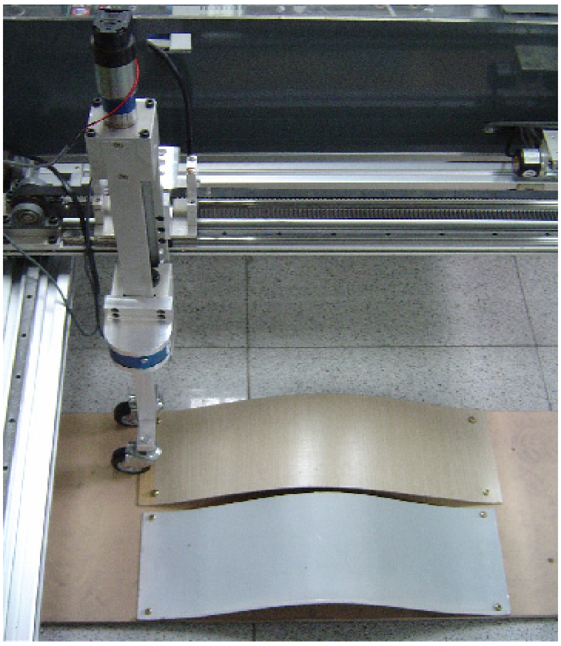

Fig 3. Experimental setup

4.2. Force tracking for wood environment

First, the proposed impedance control is tested for wood environment. Various desired forces such as 5N, 10N, and 20N are tested. Initially, the robot makes contact with the environment and starts moving. So the transition effect from free space to contact space is minimal. The impedance controller gains are set as m=0.1,b=1, and η =0.05. This adaptive gain value is selected to satisfy the stability condition as

$$0 < \eta = 0.05 < \frac{0.01}{0.01 + 0.1} = 0.09 .$$

Figure 4 shows the 5N force tracking as well as the position tracking by the impedance force control. The travelling time of the robot is about 38 seconds. Force is well regulated without losing stability. Glitches on position tracking plot are due to display problem in a PC. Actual encoder sensing values are correct. Figures 5 and 6 show 10N and 20N force tracking, respectively. All of cases show the stable force tracking and the controller is robust enough to regulate a desired force

The corresponding position trajectories show the actual shape of the environment.

1) 5N

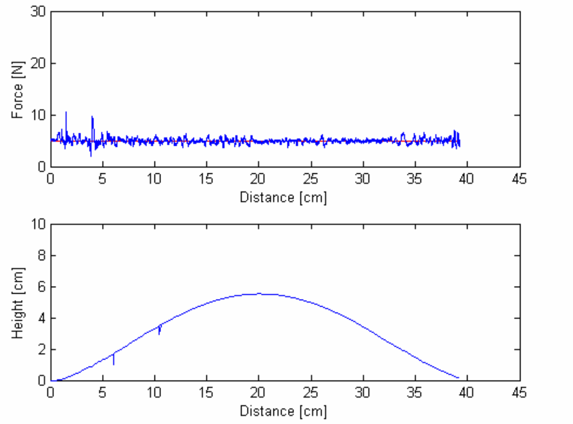

Fig. 4 Impedance force tracking control for wood

2) 10N

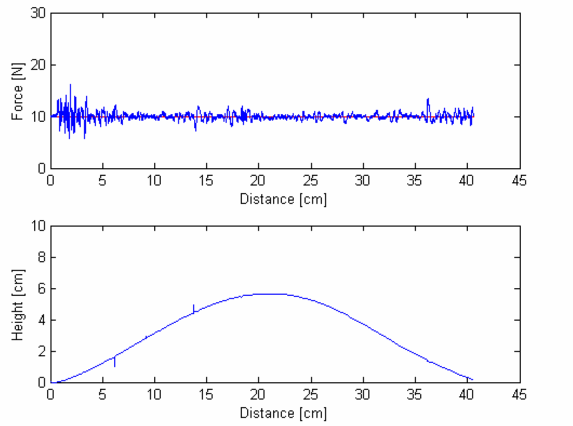

Fig. 5. Impedance force tracking control for wood

3) 20N

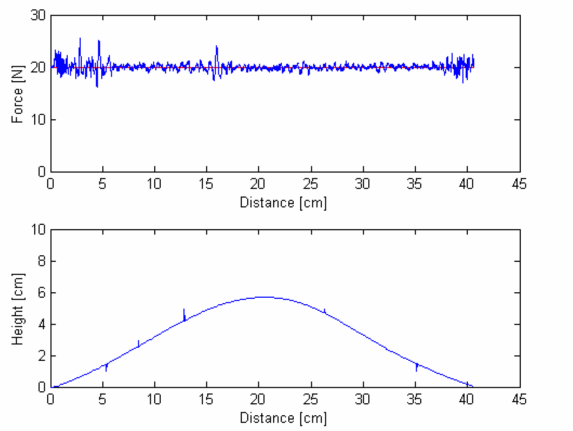

Fig. 6. Impedance force tracking control for wood

4) 20N

In this experiment, different impedance parameters are used such as m=0.1,b=10, and η=0.05. As the damping gain is increased, the stability range is also increased.

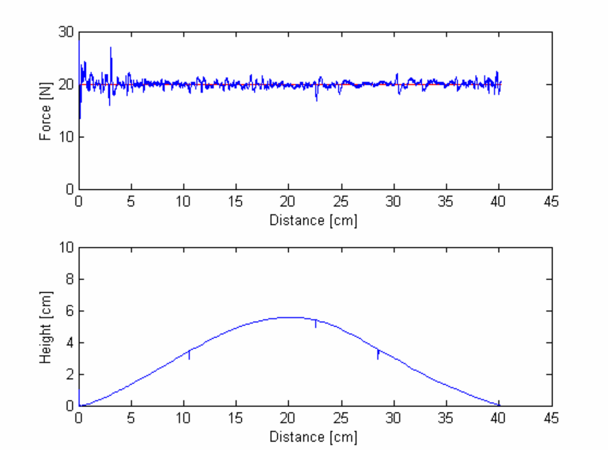

Fig. 7. Impedance force tracking control for wood

The stability bound is satisfied with

$$0 < \eta = 0.05 < \frac{0.1}{0.1 + 0.1} = 0.5 .$$

Force tracking performance is quite similar to that of the previous case as shown in Figure 7.

We have also tried for different adaptive gains which do not satisfy the bound given in (17). Force tracking performance is worse so that larger oscillatory behaviour is observed.

4.3. Force tracking for steel environment

Next experiment is done for the steel environment. Usually for the rigid environment, more compliance is given to force control in order to make the system be stable. However, here the same impedance and adaptive gains are used for this experiment. This tests the robustness of the controller to the system parameter variation.

Initially the robot makes contact with the steel environment as before. And then the robot is required to move on the steel. As before, various force values are regulated such as 5N, 10N, and 20N. Since the stiffness of the steel is much larger than that of the wood, force control becomes more difficult. The larger stiffness of the material is, the smaller displacement in position to generate the same force. This is the nature of force control.

As expected, in Figures 8, 9, and 10, more oscillatory behaviours in force tracking can be observed than the case of wood. Comparing the force tracking result of Figure 4 on the wood environment with that of Figure 8 shows that larger oscillations in force tracking can be observed in the case of the steel environment. The corresponding position tracking data are also plotted. We clearly see from position tracking data that the robot follows the steel environment well.

The controller gains for the experiment are m=0.1,b=1, η=0.05, which are the same as for wood.

1) 5N

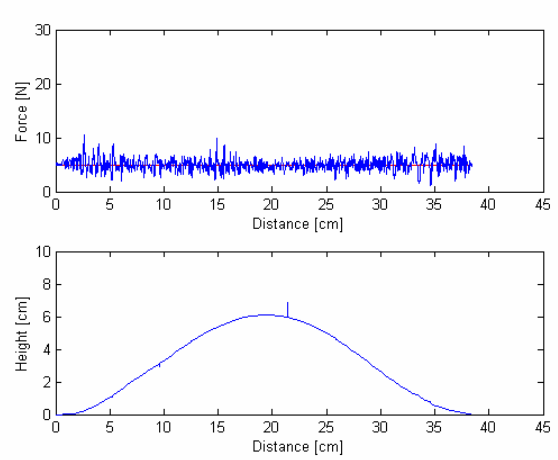

Fig. 8 Impedance force tracking control for steel

2) 10N

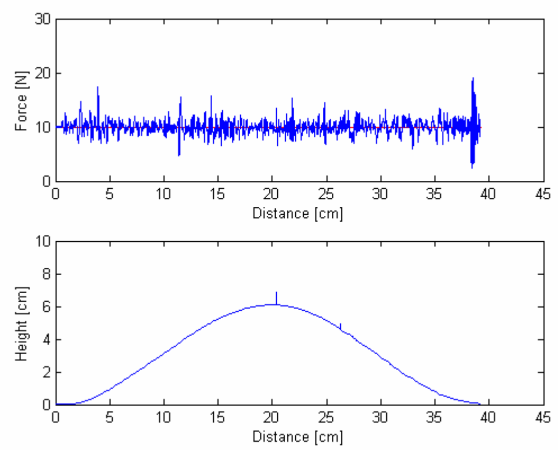

Fig. 9 Impedance force tracking control for steel

3) 20N

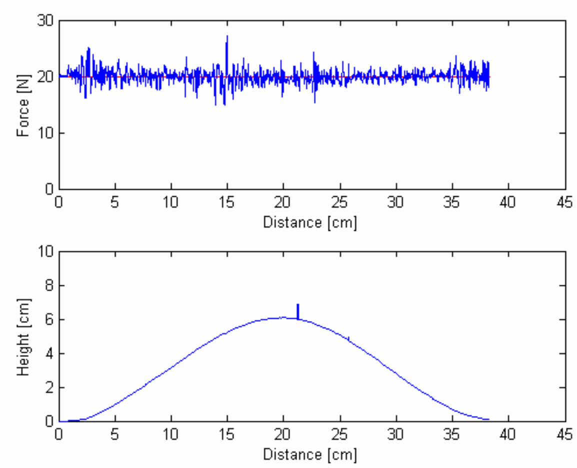

Fig. 10 Impedance force tracking control for steel

4) 20N

The different controller gains are set as m =0.1, b=10, η = 0.05. Increased damping gain gives similar tracking performance.

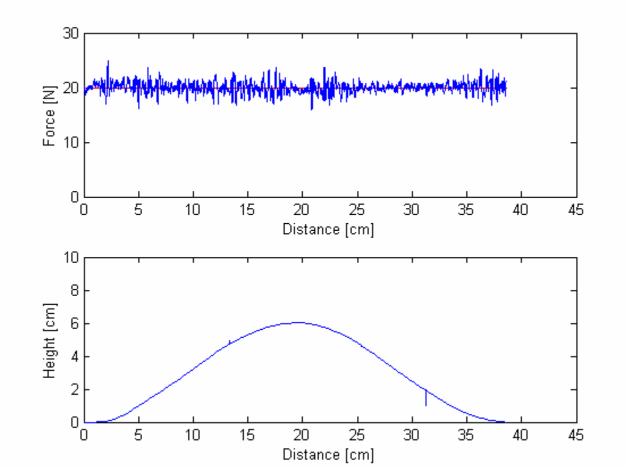

Fig. 11 Impedance force tracking control for steel

4.4. Force tracking for both wood and steel

The last experiment is to track on both wood and steel by making transition from free space to contact space. The robustness of the controllers is tested under unknown stiffness without changing controllers' gains. Figure 12 shows the force tracking result by the proposed control method. As shown in Figure 12, the initial position of the robot is located about 2 cm above the ground.

The robot starts moving toward the ground and makes contact at about 2secs. So the large force overshoot can be observed at the contact. And then the robot follows the wood environment and the steel environment while regulating force. The whole travelling time is about 2 minutes. Even if the large force overshoot occurs at initial contact, force is well maintained without losing its stability. Position tracking plot shows the actual tracking shapes of the wood and steel environment of the robot. We clearly see from Figure 12 that force tracking is quite good.

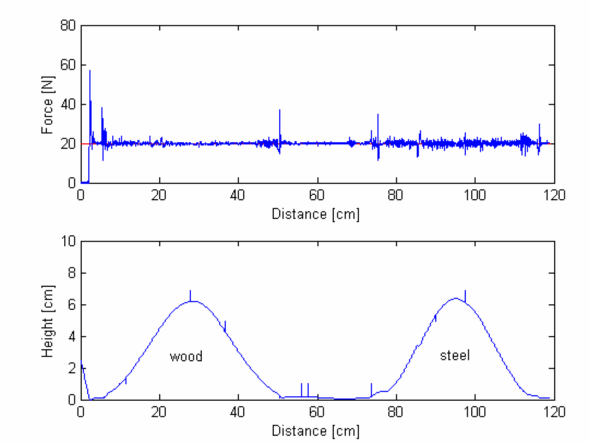

Fig. 12 Impedance force control for wood and steel

5. CONCLUSIONS

In this paper, impedance force control algorithm has been applied for a crack sealing robot to regulate contact force on the ground. Force control is required to have good cleaning task of crack. Even though surface condition of the environment is totally unknown to the robot, performance of impedance force tracking is quite good. The following issues have to be addressed in the future

- Experiments have to done outdoor environment of real road surface conditions.
- Force control is tested by attaching a real brush.
- Power source should supply stable power to the system.

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