Experimental Studies of Two Force Control Algorithms for a Crack Sealing Robot in Highway Maintenance Technology

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Abstract: This paper presents experimental studies of force control algorithms for a crack sealing robot. The crack sealing robot is built as a test-bed to regulate contact force on the ground for a better task. Force tracking performances of two main force control algorithms, explicit force control and impedance force control, are compared experimentally. Experiments are conducted to test the robustness of control algorithms under unknown surface condition of the road. Experimental results show that performances of two force control algorithms are very comparable.

Keywords : crack sealing robot, impedance force control, explicit force control

1. INTRODUCTON

Works at the road are very dangerous jobs for workers due to fast passing cars. To protect workers from dangerous situation on the road, automation of the whole working process by reducing the number of workers at present working environment will be one solution. There have been extensive researches of autonomous maintenance and construction for highway in the USA. The advanced highway maintenance and construction technology (AHMCT) center at UC Davis is one of the leading groups in this field. Their main goal is to automate all the maintenance works related with highway.

Recently, as a project, they have built a crack sealing automobile that seals cracks on the highway by following almost straight line of cracks [1]. The purpose of the crack sealing automobile is to seal cracks on the pavement autonomously. Cracks may cause uncomfortable driving condition to the driver, even the deadly traffic accident.

In the similar way, an autonomous crack sealing robot is built for feasible application. Before sealing crack, the crack must be detected by a laser sensor and a camera sensor, then cleaned for a better sealing job. To perform a brushing task before sealing, force control to the ground is applied to maintain constant contact.

The hybrid force control and the impedance force control are two main streams [2,3]. Based on these two control strategies, various modified force control algorithms have been proposed [4-6]. The explicit force control algorithm is formulated from a simple PID control of force errors [6]. The force tracking impedance control algorithm has been proposed to specify a desired force directly and to perform force tracking under unknown environment [7-8]. The fuzzy and neural force control methods to deal with unknown environment have been proposed [9, 10].

In this paper, as an extension of our previous researches, experimental studies are conducted to confirm the theoretical analysis [8,11-12]. Performances of the force tracking impedance control and the explicit PID control algorithm are tested. The sealing robot is required to maintain a desired force by following the trajectory on the curved wood and the curved steel environment. To test the robust performance on the unknown environment of the proposed force control algorithms, the environment is designed as the curved shape which is arbitrarily unknown 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.

Extensive experimental studies of two main force control algorithms, the impedance force control and explicit force control, are conducted. Experimental results show that two controllers are very robust under unknown environment uncertainties. Performances of two force control algorithms are quite good and stable under unknown environment. It turns out that the explicit PID force control method is better in implementation point of view while less contact force is observed under the impedance control method. In force tracking, two control methods are comparable.

2. OVERALL SYSTEM STRUCTURE

The developed overall crack sealing robot structure

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is shown in figure 1. The robot is a kind of wheeled drive robots equipped with a gantry typed xyz 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 hidden in a black box has a laser sensor and a camera sensor to detect cracks. Abrupt step change of the crack in sensed information by the laser sensor is obtained by the camera.

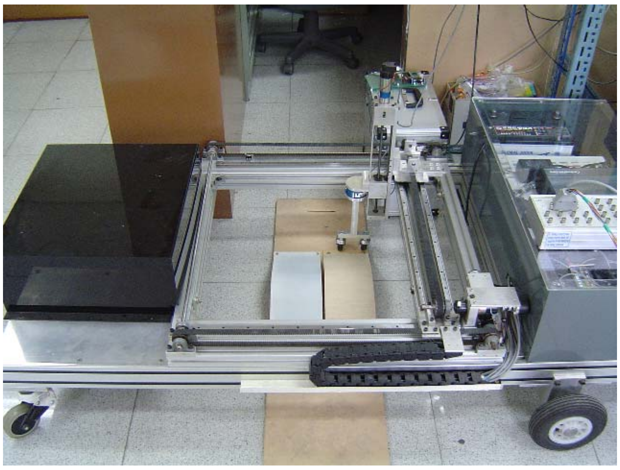

Fig. 1. Overall system structure

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 aligned in the middle of the robot wheels. In this way, the robot tracks the crack. The crack sealing part has a gantry typed robot that moves xyz directions. The force sensor is attached to the end of the z axis so that the normal force to the ground is regulated. The brushing device will also be equipped at the end of z axis in the near future. 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.

3. IMPEDANCE FORCE CONTROL ALGORITHM

The impedance control method regulates force by selecting impedance parameters correctly. Even though it has lack of force tracking capability, the dynamic relationship between the robot and the environment is considered. Here, the force tracking impedance control is summarized [7,8,10-12].

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, f_e is the external force, and m, b, k are impedance gains. By setting appropriate gains, a desired force can be achieved.

To give the force tracking capability to the robot, equation (1) can be reformulated as

$$f_e - f_d = m\ddot{\varepsilon} + b\dot{\varepsilon} \,. \qquad (2)$$

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

Since the external force can be modeled as the spring system $f_e = -k_e\varepsilon$, substituting it into equation (2) becomes

$$-f_d = m\ddot{\varepsilon} + b\dot{\varepsilon} + k_e\varepsilon \,, \qquad (3)$$

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 $\varepsilon' = \varepsilon + \delta x_e$, replacing ε with ε' at (3) yields

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

δx_e can be minimized to a certain accuracy by the user.

However, if f_d and x_e are time varying, there will be a force tracking error. The force has the error in tracking a desired force. To make $f_e = f_d$ at (4), the simple adaptive method has been proposed as below. Equation (4) can be reformulated as

$$m\ddot{\varepsilon}' + b(\dot{\varepsilon}' + w) = f_e - f_d \,, \qquad (5)$$

where

$$w(t) = w(t-\lambda) + \eta \frac{f_d(t-\lambda) - f_e(t-\lambda)}{b} \,, \eta > 0 \,, \qquad (6)$$

η is an adaptive gain and λ is the sampling time.

The stable condition of an adaptive gain can be found as

$$0 < \eta < \frac{b\lambda}{b\lambda + m} \,. \qquad (7)$$

More detailed stability analysis of this algorithm can be found in the paper [7].

The adaptive impedance force control block diagram is shown in figure 2. Since the z axis of the gantry robot is force controlled and 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 as below

$$\tau = \frac{1}{m}[b(\dot{\varepsilon}' + w) + f_d - f_e]. \quad (8)$$

Figure 2 shows the control block diagram of the impedance force control algorithm.

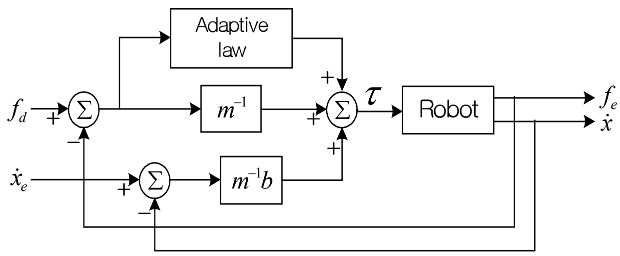

Fig. 2. Proposed impedance control

4. EXPLICIT PID FORCE CONTROL ALGORITHM

The explicit PID force control algorithm is a kind of the hybrid force control method that has a position-controlled direction and a force controlled direction selected by a selection matrix. Here, for simplicity, the crack sealing robot has only z direction to be force controlled. So, the controller for the force-controlled direction is formed as a PID controller type that is formed with force errors.

The control law is given as

$$\tau = k_P e + k_D \dot{e} + k_I \int e dt \quad (9)$$

where f_d is a desired force and k_P, k_D, and k_I are controller gains.

The control block diagram is depicted in figure 3.

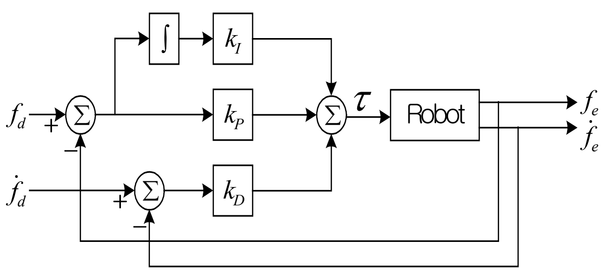

Fig. 3. The explicit PID control block diagram

5. EXPERIMENTS

5.1. Experimental setups

The force control experimental setup is shown in figure 4. Environment is made of wood and steel to have unknown stiffness, and has the round shape to give unknown environment location to the robot. Since z axis is actuated by a ball screw driven by a dc motor, the gravity force of the robot is compensated. Considering one axis control, Coriolis and centrifugal forces can also be neglected. Since the robot is very much linearized for a force tracking task, the dynamic compensation for the robot 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 and rollers are attached to the end-effector to minimize friction force. The normal force to the ground is regulated. The sampling time is 10ms.

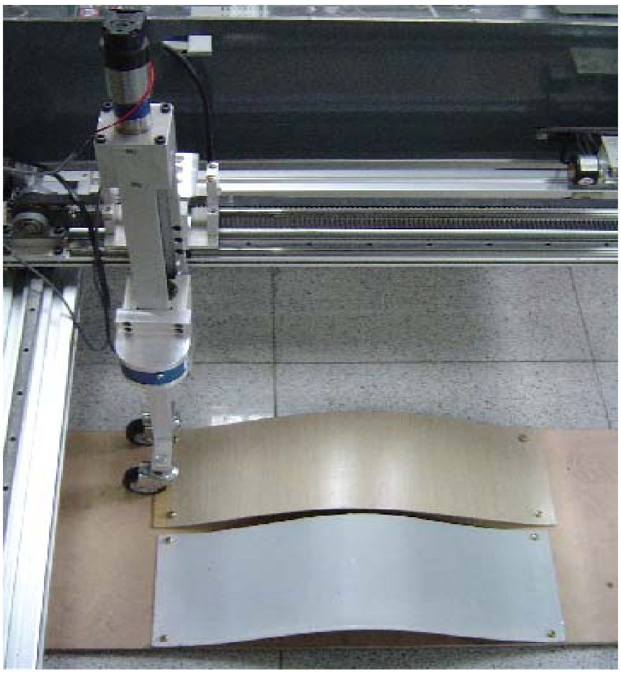

Fig. 4. Experimental setup

5.2. Force tracking for wood environment

First, force control algorithms are tested for the wood environment. The desired force is 20N. Initially, the robot already made contact with the environment. So the transition effect from free space to contact space is minimized.

1) PD control

The explicit PD force control is tested to regulate contact force. The controller gains are *kp* = 20 and *kd* = 0.2. Fig.5 shows the tracking results for force and position. The controller maintains the stability, but we clearly see that force tracking errors are observed. The shape of wood environment is clearly shown. We see that more force is detected in climbing up direction and less force is detected in climbing down direction. Next, to minimize the force tracking error, the PID controller is used.

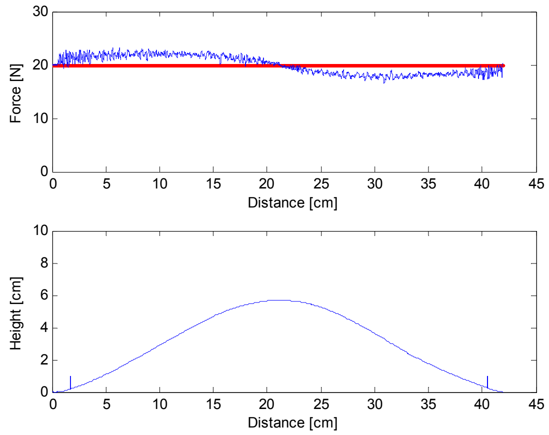

Fig. 5. Tracking results of PD control

2) PID control

To eliminate those tracking errors, PID controller is used. The controller gains are selected as *kp* = 20, *kd* = 0.2, and *ki* = 0.2. The tracking results are shown in figure 6. We clearly see that tracking errors are minimized.

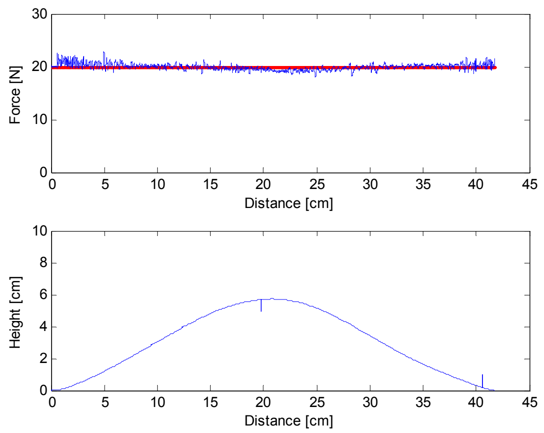

Fig. 6. Tracking results for PID controller

3) Impedance control

The impedance controller gains are set as m=0.1,b=1, η=0.05.

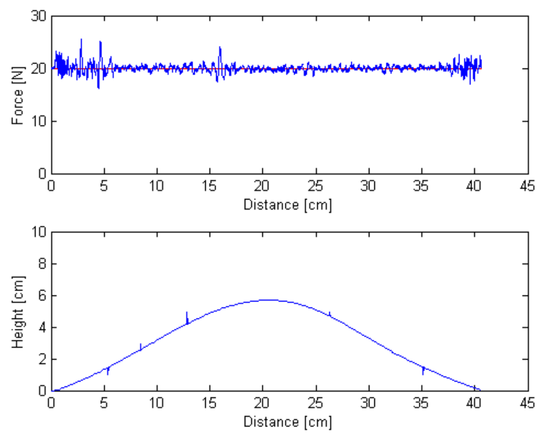

Fig. 7. Impedance force tracking control for wood

This adaptive gain value is selected to satisfy the stability condition given in (7) as $0 < \eta = 0.05 < \frac{0.01}{0.01 + 0.1} = 0.09$.

Figure 7 shows the 20N force tracking as well as the position tracking by impedance force control. The traveling time of the robot is about 40 seconds. Force is well regulated at 20N without losing its stability.

5.3 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 to make the system stable. Initially, the robot made contact with the steel environment as before. And then the robot is required to move on the steel. As before, a force value is regulated as 20N. Since the stiffness of the steel is much larger than that of the wood, force control becomes more difficult.

1) PD control

The controller gains are *kp* = 20, *kd* = 0.2, and *ki* = 0. As expected, in figure 8, more oscillatory behavior in force tracking can be observed. Force tracking errors are still present. Deviated tracking error is similar to that of figure 5, but it is more oscillatory. These errors can be minimized by I controller of the PID controller.

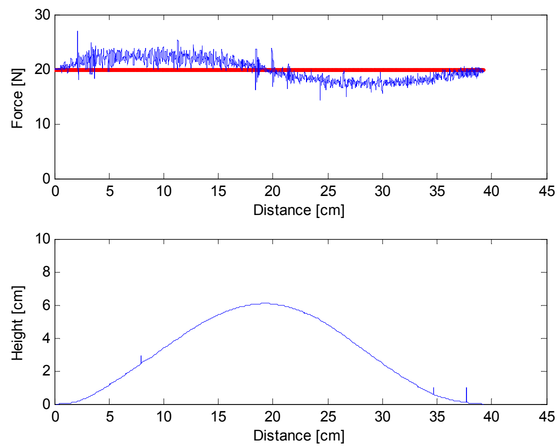

Fig. 8. Tracking results for PD control

2) PID control

The PID controller gains are *kp* = 20, *kd* = 0.2, and *ki* = 0.2. In figure 9, the force tracking error is eliminated. The corresponding position plot is also shown. Glitches appeared in position tracking plots are due to plotting problem in PC. Those should not be considered as actual data.

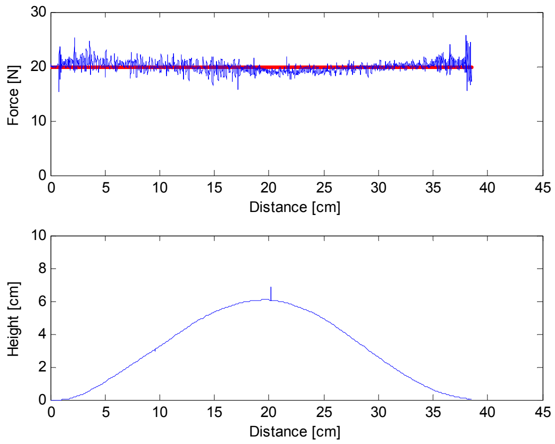

Fig. 9. Tracking results for PID control

3) Impedance control

Comparing the force tracking result plots of figure 7 and figure 10 shows that larger oscillation in force tracking can be observed in the case of 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.

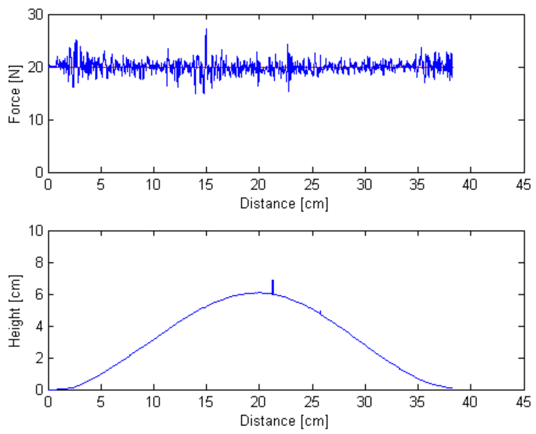

Fig. 10. Impedance force tracking control for steel

5.4. 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

The initial position of the robot is located about 2 cm above the ground. The robot starts moving toward to the ground and makes contact at about 2secs. So the large force overshoot can be observed at contact in figures 11 and 12. And then the robot follows the wood environment and the steel environment while regulating a desired force. The whole traveling time is about 2 minutes.

1) PID control

Even if the large force overshoot occurs at initial contact, the 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. Force overshoot in the middle occurs due to the irregular surface condition.

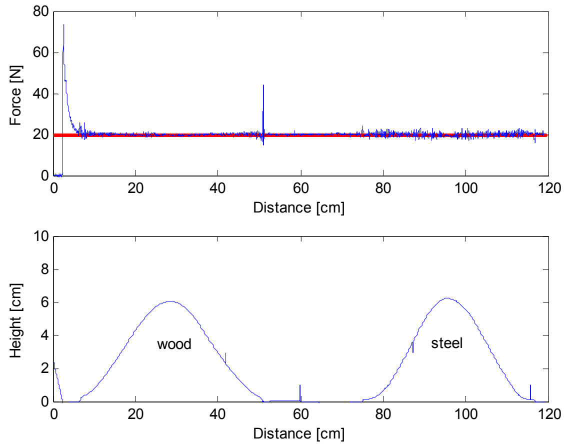

Fig. 11. PID force tracking control for steel

2) Impedance control

Figure 12 shows the force tracking result by the impedance control method. We clearly see from figure 12 that force tracking is quite good. As expected, force tracking for wood environment is better than that for steel environment. Contact force is somewhat smaller than that of figure 11.

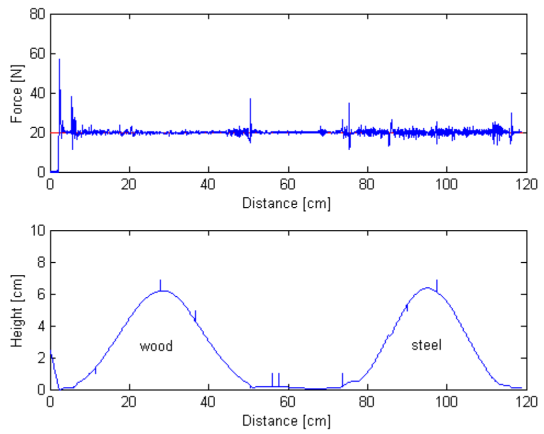

Fig. 12. Impedance force control for wood and steel

6. CONCLUSIONS

This paper presented experimental studies of the force control algorithms for the crack sealing robot. The crack sealing robot is developed to find crack and tracks crack on the pavement while the contact force on the ground is regulated. Impedance force control algorithm and explicit force control algorithm are tested under unknown environment. Two force control methods performed stable force tracking under unknown environment stiffness and location. The explicit force control has an advantage in implementation because only force information is required, while impedance control requires both position and force information. However, impedance force control shows less contact overshoot.

In the future, experiments will be conducted on real pavement outside.

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