Experimental Studies of Force Control for Crack Sealing Robot

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Abstract: In this paper, experimental studies of force tracking control for the crack sealing robot are presented. Crack sealing robot is built to detect, track and seal the crack on the pavement. Before sealing, crack must be detected by a laser sensor and a camera sensor, then cleaned for a better sealing job. In order to maintain contact with the ground force control is required to brush all dirt in the crack out for preparing sealing cracks with tars. Impedance control algorithm is presented to regulate a specified desired force. Experimental studies of the proposed force control algorithm are conducted under unknown environment stiffness and location. Performances of force control algorithm are stable and excellent.

Keywords: Crack sealing robot, Impedance force control, Uncertainties

1. INTRODUCTION

Autonomous maintenance and construction technology is now demanded in order to give better standard of driving. Works at the road are very dangerous jobs for workers due to fast passing cars. In order to reduce the open dangerous situation on the road, automation of the whole working process by reducing the number of workers at present working place 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 group in the world for this kind of works. Their works are mainly to automate all the maintenance work of highway. The sealing robot is one of them [1]. Recently, they have built a crack sealing automobile that seals cracks on the highway by following almost straight line of cracks [1]. Cracks on the pavement appear at the boundary of where two separate paving jobs are done by the paver. Cracks cause uncomfortable driving environment to the driver, even the traffic accident.

In this paper, an autonomous crack sealing robot is developed. In order to perform brushing task before sealing, force control to the ground is applied to maintain constant contact. The crack sealing robot finds crack by using a laser sensor and a vision sensor, and tracks the crack on the pavement while contact force on the ground is regulated. Force control is known as a sophisticated control method that has to control the force as well as the position of the robot.

Force control became more attractive since many tasks with robots are required to deal with environment : human, machines or objects. There have been many force control algorithms proposed. The hybrid force control and the impedance force control are two main streams. The hybrid force control can specify desired force directly, but has lacks of dynamic relationship between the robot and the environment [2]. On the other hand, the impedance force control does not specify desired force directly, but the dynamic relation is considered [3].

Based on these two control strategies, various modified force control algorithms are proposed [4-6]. Jung and Hsia have proposed force tracking impedance control algorithm that can specify a desired force directly, and perform force tracking under unknown environment [7-8]. The idea is so simple that implementation can be done so easily. Kiguchi et. el. have proposed a fuzzy force control method to deal with unknown environment [10]. Jung et. el. have proposed the neural force control algorithm that can compensate for all the uncertainties under unknown environment by using neural network [11].

In this paper, performances of the proposed force tracking impedance 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. In order to test the robust performance of the proposed force control algorithm, environment is designed as a curved shape to give 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.

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. FORCE CONTROL ALGORITHM

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. The adaptive impedance force tracking method proposed by Jung et. el. solves this force tracking problem. Here we briefly formulate the proposed impedance control method. The detailed contents can be found in the paper [7].

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The original impedance control of the closed loop equation can be formed as

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

where $\varepsilon = x_e - x$ and x_e is the environment location, x is the actual location, f_e is the external force. m, b, k are impedance gains. By setting appropriate gains, desired force can be achieved.

In order to have force tracking capability, equation (1) can be formed differently by setting the stiffness gain $k = 0$ and subtracting desired force f_d such that

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

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

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

where k_e is the environment stiffness.

Without knowing the exact stiffness k_e, $f_e = f_d$ is assured at the steady state. In order for the robot to have the over-damped response, m and b gains are selected as approximated values by the relation

$$b > 2\sqrt{mk_e} \qquad (4)$$

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

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

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

If x_e is constant, then $\dot{x}'_e = \ddot{x}'_e = 0$. Equation (5) becomes

$$m\ddot{x} + b\dot{x} = f_e - f_d \qquad (6)$$

Therefore, at the steady state, $f_e = f_d$ can be obtained. However, if f_d and x_e are time varying, there will be force tracking error. The force has the error term as $f_e = f_d - m\ddot{x} - b\dot{x}$.

In order to make $f_e = f_d$, the simple adaptive method is proposed as below.

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

where

$$w(t) = w(t-h) + \eta\frac{f_d(t-h) - f_e(t-h)}{b}, \eta > 0 \qquad (8)$$

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

We have analyzed the stability of the equation (7) and found the stable condition of an adaptive gain as

$$0 < \eta < \frac{bh}{bh + m} \qquad (10)$$

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

The simplified control block diagram is shown in figure 1. Since the only normal force is regulated by z axis, the robot dynamics can be considered as a simple linear system. So here dynamic compensation proposed as in the paper [7] is not considered.

So the control law becomes

$$u = \frac{1}{m}[b(\dot{\varepsilon}' + w) + f_d - f_e] \qquad (11)$$

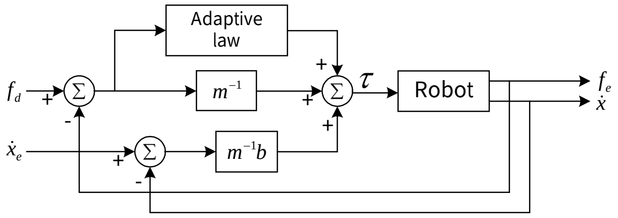

Fig 1. Proposed impedance control

3. OVERALL SYSTEM STRUCTURE

The overall crack sealing robot structure is shown in figure 2. The robot is 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 has a laser sensor and a camera sensor to detect cracks. Abrupt step change of the crack in sensed information by laser sensor is obtained by the camera.

Fig. 2 Overall system structure

The position of the detected crack can be transformed to the robot coordinate to drive wheels to make the crack position be 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 z axis so that normal force to the ground is regulated. The brushing device will also be equipped at the end of z axis in the future.

Two rollers are distantly located each other enough because the crack will be located between two rollers. The actuation part has batteries, computers, actuating motors, and other necessary hardware.

4. FORCE CONTROL EXPERIMENTS

4. 1 EXPERIRMENTAL SETUP

Force control experimental setup is shown in figure 3. Environment is made of wood and steel to have unknown stiffness, and has the round shape to give unknown location.

Since z axis is actuated by a ball screw driven by a dc motor, gravity force is minimal. Considering one axis control, Coriolis and centrifugal force can also be neglected. Sine the robot is very much linearized for force tracking task the dynamic compensation is not considered.

The robot does not have any knowledge about the environment. The robot is required to track the environment with regulated force. JR3 force sensor is used to detect force and rollers are attached to the end-effector to minimize friction force. Normal force to the ground is regulated. The sampling time is 10ms.

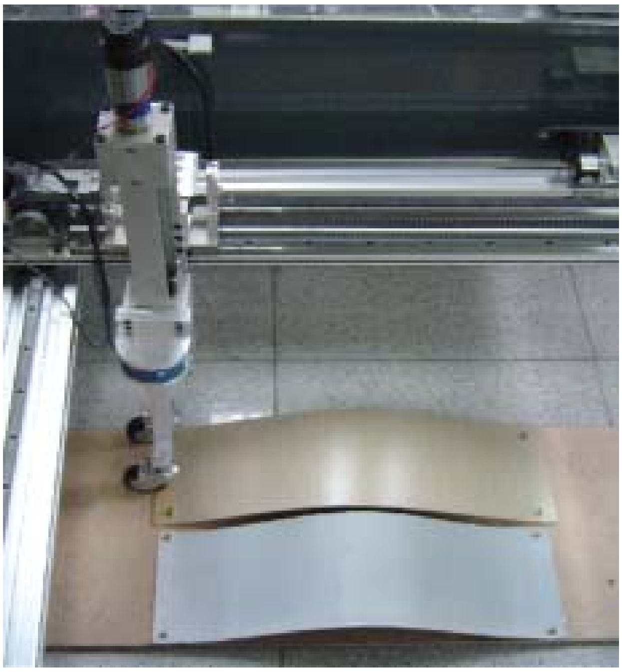

Fig. 3 Force control experimental setup

4. 2 FORCE TRACKING FOR WOOD ENVIRONMENT

The proposed impedance control is tested for wood environment. Various desired forces are tested as 5N, 10N, and 20N. Initially, the robot is made contact with the environment and starts moving. So the transition from free space to contact space is not considered. The controller gain are set as m=0.1,b=1, η =0.05. This value satisfies 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 position tracking by impedance force control. The traveling time of the robot is about 42 seconds. Force is well regulated without losing stability. Figures 5 and 6 show 10N and 20N force tracking, respectively. All of cases show stable force tracking and the controller is robust enough to regulate desired force tracking.

The corresponding position trajectories show the actual shape of the environment. Overshoots at position tracking plot are from encoder sensor measurement due to surface conditions of the wood.

1) 5N

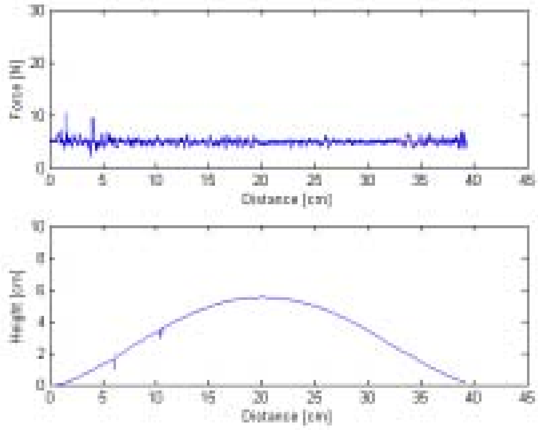

Fig. 4 Impedance force tracking control for wood

2) 10N

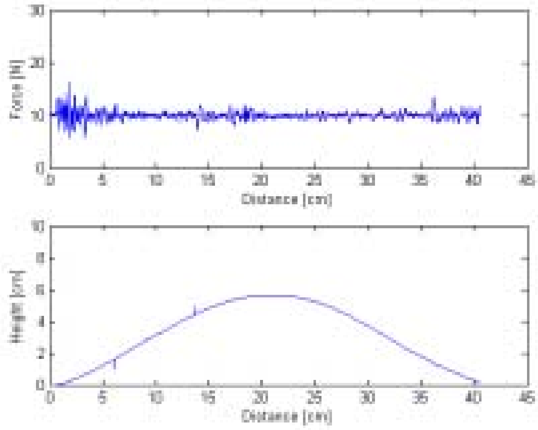

Fig. 5 Impedance force tracking control for wood

3) 20N

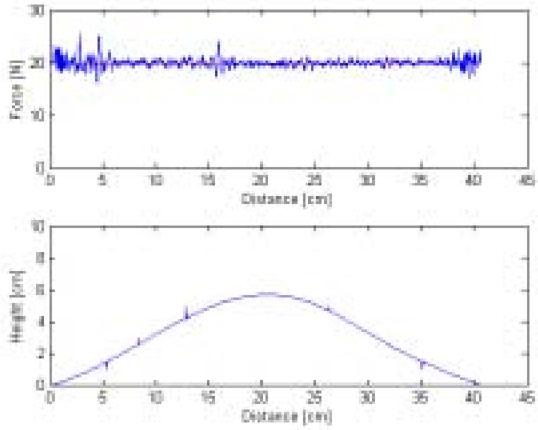

Fig. 6 Impedance force tracking control for wood

4) 20N

In this experiment, different impedance parameters are used as m=0.1,b=10, η=0.05. As the damping gain is creased, the stability range also increased. The stability bound is satisfied as $0<\eta=0.05<\frac{0.1}{0.1+0.1}=0.5$. Force tracking performance is quite similar to that of the previous case as shown in figure 7.

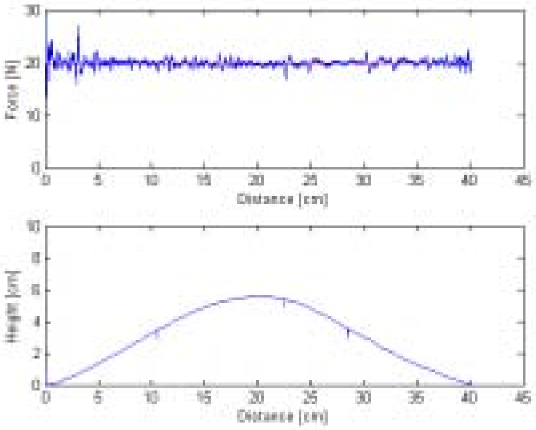

Fig. 7 Impedance force tracking control for wood

We have also tried for different adaptive gains which do not satisfy the bound in (10). Force tracking performance is worse that oscillatory behavior is observed. Even though the condition (10) is satisfied when ideal dynamic compensation is done, the approximate boundary value also satisfies the condition.

4.3 FORCE TRACKING FOR STEEL ENVIRONMENT

Performances of force tracking on wood environment are very good. 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 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 is made 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 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 behavior in force tracking can be observed than the case of wood. However, in all of cases, stable force tracking is achieved. Comparing the force tracking result of figure 4 on the wood environment with that of figure 8 shows that larger oscillation in force tracking can be observed in the case of steel environment.

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

1) 5N

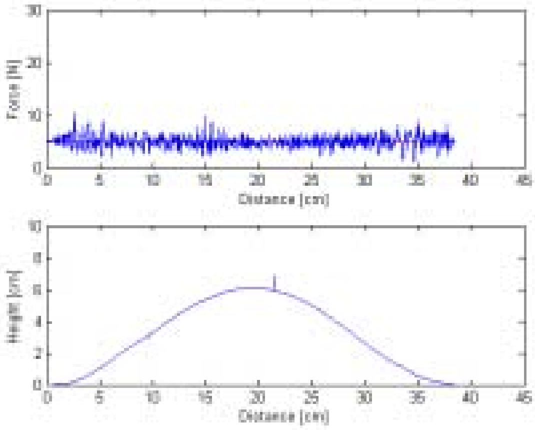

Fig. 8 Impedance force tracking control for steel

2) 10N

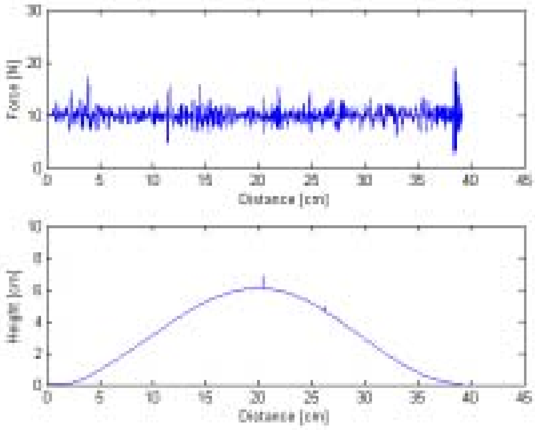

Fig. 9 Impedance force tracking control for steel

3) 20N

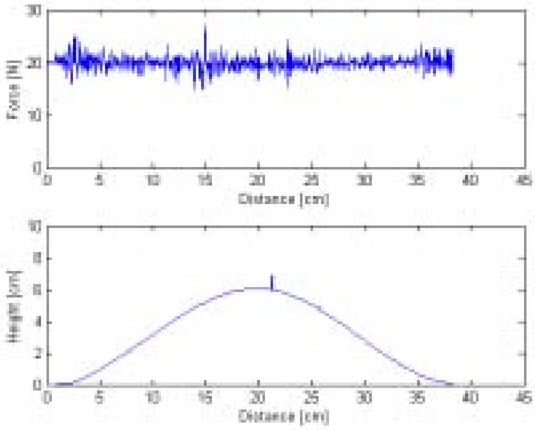

Fig. 10 Impedance force tracking control for steel

4) 20N

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

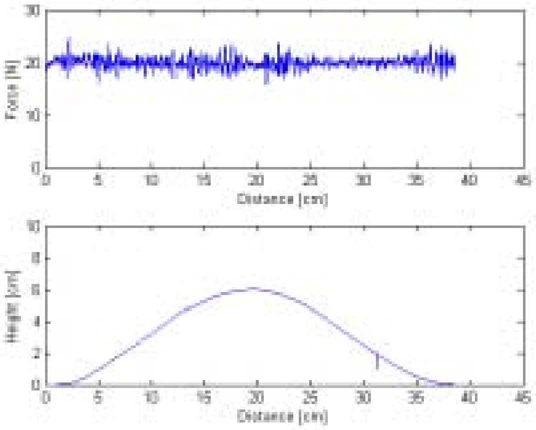

Fig. 11 Impedance force tracking control for steel

4.4 FORCE TRACKING FOR WOOD AND STEEL

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 to the ground and makes contact at about 2secs. So the large force overshoot can be observed at contact. And then the robot follows the wood environment and the steel environment while regulating force. The whole traveling 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 very good.

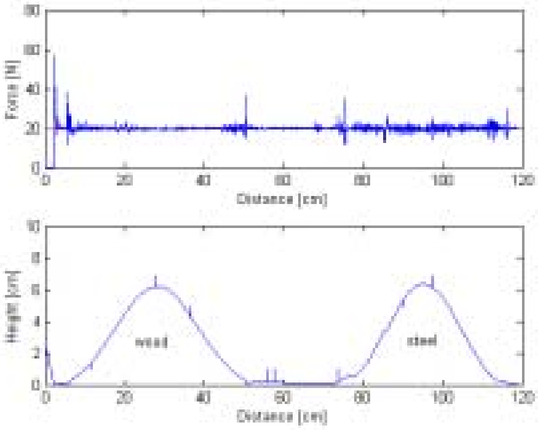

Fig. 12 Impedance force control for wood and steel

5. CONCLUSIONS

This paper presented experimental studies of force tracking impedance force control algorithm for the crack sealing robot. The crack sealing robot is developed to find crack and tracks crack on the pavement while contact force on the ground is regulated. Impedance force control algorithm is tested under unknown environment. The proposed force control method performed stable force tracking within the stability bound of the adaptive gain. Even though the dynamic compensation is not considered in this paper, performances of force tracking of the proposed control under unknown environment stiffness and location are excellent. Even though the environment is changed from wood to steel, the controller successfully maintains contact and regulates desired force.

Compensating for dynamic uncertainties may improve the force tracking performance much better.

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