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Task-oriented Impedance Control for Integrated Autonomous Cleaning Manipulator

Guangli Sun, Peng Li, Zhi Chen, Zhen Yu, Yang Zhou, Linzhu Yue, Yun-Hui Liu

***Abstract*— While the development of the autonomous system for dangerous high-rise cleaning is stuck by the energy supplement, it opens up challenges to the development of a simple and efficient manipulator and the control strategy of these manipulators. In this paper, an integrated autonomous cleaning manipulator has been designed, and for a better control performance of dirt removal, a task-oriented impedance control algorithm has been proposed. The mechanical design of the *IACM* not only fulfills the whole steps of the manul cleaning surface, guarantees the cleaning effects of the system, but also by adding water recycle system in it makes the system simpler, lighter and more environmentally friendly. Through using the feedback of the dirt removal model and impedance model, the proposed control algorithm connects the relationship of the dirt to manipulator joint control, which gives a direct relationship of the cleaning effects and the manipulator control. The experimental results comparison of the constant interaction force and the task-oriented interaction force show the proposed method is more energy-saving and more efficient. This control method can also be widely extended to other surface machining area.**

I. Introduction

Window cleaning is a tedious and intensively repeated task, autonomous robots for window cleaning has been developed with different kinds of mechanisms, like rope-climbing [1], autonomous unmanned vehicle, wall-climbing robot [2], humanoid robot [3] etc. However, no matter what kinds of implementations, the greatest obstacle is the power supplement of the system. Robots in the high-rise environment consumes a large amount of energy to reach and stay at the working height, the energy left for cleaning operations is in great limitation. Even though continuous energy can be transmitted to the robot through cables, in this case, the stability and safety of the robot would be decreased as quite long cables are needed for electricity transmission [4]. Therefore, under the limited power supplement, the workspace is largely limited, the automation level are limited, added with the cost on the robot maintenance, even though the manual operations are quite dangerous, autonomous robots for high-rises cannot be accepted by the market and people.

In window cleaning, the consumption of energy comes from three aspects [5]: robot locomotion in the space, the movement of the manipulator motors and the cleaning operations of the end effector motors. Since the good and bad of the high-rises locomotion mechanisms are still in debate, the focus of the energy saving has to be transferred to the manipulator and the end effector. Comparing with the large work surface, the workspace of the manipulator and the end effector is too small [6], which causes the frequently repeated operation of the manipulators, so that the energy saving can be considered in two aspects:1. optimal trajectory path planning [7], [8]; 2, Energy-saving of the manipulator depends on finding a good method to decrease the energy consumption of every operation loops. Trajectory planning is largely limited by the locomotion flexibility. The reliable roadmap for energy consumption is to decrease the manipulator energy consumption.

Window cleaning is a typical environment interaction operations, the interaction with the working surface directly decides the working quality and influences the working efficiency. Impedance control of the window cleaning work has been studied in the [9], [10]. In the impedance control, the impedance control model helps us build the relationship between the interaction environment and the manipulator. Recent researchers broaden the impedance control onto rehabilitation, and human-robot interaction work [11], adaptive control method has been used for unknown environment information and the dynamic interaction [12]. Most popular research now, is to use iterative learning method [13] or other reinforcement learning method [14] to solve the unknown model parameters problem.

For the window cleaning task, the unpredictable dirt type is a problem. The varying dirt types problem, is often solved by different kinds of cleaning method in other cleaning systems, like Ion removal or nano cleaning cloth, however, pre-calibrated cleaning force and velocity should be defined in the system to guarantee the cleaning quality, no direct method has been proposed for handling unknown dirt, especially for the stain which is not easy to clean. Extending the problem to the larger market task, deburring or derusting, is also faced with the removal difficulty. Therefore, a more flexible and adaptable method should be given to solve this kind of problem. Interaction operations to deal with the unpredictable dirt is still with no research result, however, since the force and cleaning velocity cannot be predicted in the field, but the constant impedance force, can not make sure the dirt can be removed efficiently, the accumulation of the repeated work, will consume a large number of energy, so that we should improve the cleaning efficiency by solving the unpredictable dirt. In this paper, we will solve this problem from two aspects, firstly, the mechanical design; secondly,

G. Sun, Z. Chen, Z. Yu, Y. Zhou, L. Yue and Y.-H. Liu are with the Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong. P. Li is with the School of Mechanical Engineering and Automation, Harbin Institute of Technology (Shenzhen). This work was supported in part by the VC Fund 4930745 of the CUHK T Stone Robotics Institute, and in part by the Shenzhen and Hong Kong Joint Innovation Project under Grant no. SGLH20161209145252406.

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the dirt cleaning oriented impedance control method will be proposed.

The contribution of this paper divides into three aspects:

1) an Integrated Autonomous Cleaning Manipulator is designed and verified in the real windows cleaning situation;
2) a task-oriented impedance control scheme for *IACM* control has been proposed, which can be widely extended to other surface machining area;
3) overall experimental results have shown that the control scheme can sufficiently keep the working effectiveness while giving a less energy consumption.

This paper is arranged as follows: section II will introduce the detail mechanical structure of the *IACM*; section III modeling will introduce the model of the dirt removal model, the impedance control model. and the task-oriented Impedance Control for *IACM*; after that, the comparison of the constant impedance control and the task-oriented impedance control is shown in section IV; Conclusion and future work are in section V.

II. Mechanical design of *IACM*

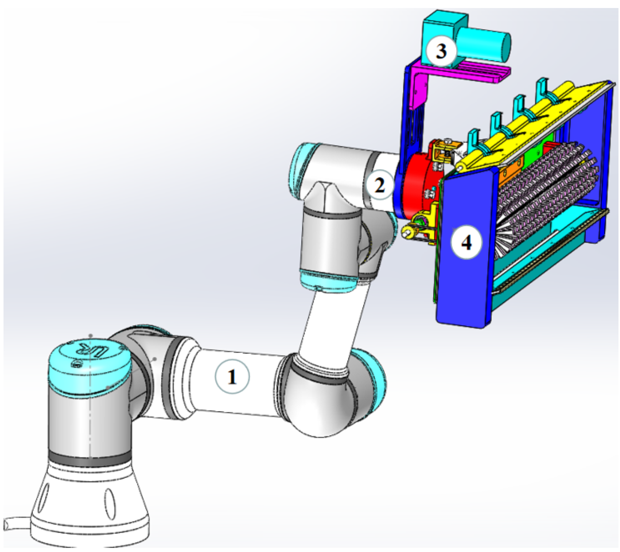

Fig. 1. 3D Model of Integrated Autonomous Cleaning Manipulator *IACM*. ① is the robotic arm; ② is the force sensor installed at the TCP of the robotic arm; ③ is the detection camera; ④ is the self-designed cleaning unit.

The Integrated Autonomous Cleaning Manipulator(*IACM*) consists of a robotic arm, a camera, a force sensor and a cleaning unit, which is shown in 1. Manual operations always consist of the following steps to guarantee the window cleaning effects:

1) spraying the cleaning detergent on the window surface;
2) brushing the window with the wet mop for eliminating dirt;
3) using the scraper to remove the residual water and detergent.

Drawing on the experience of the manual operations, the overall structure of the window cleaning unit is shown in

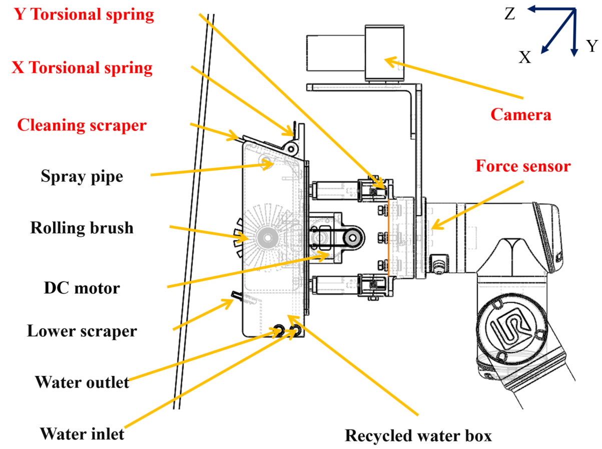

Fig. 2. Mechanical Structure of Integrated Autonomous Cleaning Manipulator *IACM*.

Fig. 2. This cleaning unit integrates water spraying, water squeezing, water collection and compliant contacting functions, and can be installed at the end of the lightweight robotic manipulator to conduct window cleaning task.

In order to make full contact between the cleaning unit and the window, a compliant mechanism is applied as shown in Fig. 2. A X axis rotational achieves the compliant contact of the cleaning scraper with the window by a group of X torsional spring links. While, two Y torsional springs are linked in the last robotic joint links to give a Y axis rotational compliance, such that the cleaning head can adjust to the Y axis sloping surface. It is easier and more convenient to achieve a compliant contact based on these passive torsional spring mechanism compared with the positive control method. Meanwhile, the torsional springs on the scraper link make it possible to adjust the scraper to a proper scraping angle so that it can clean the window adequately. A force sensor, which is installed between the UR link and the cleaning unit, are used as the feedback information for the interaction control between the cleaning unit and the window. The camera of this cleaning unit is adapted to detect the dirt and helps to value the cleaning results. The cleaning unit works in the following sequence. First, the sewage pump is opened to transport the used water from the sink to the water tank via a filter to remove slightly big impurity. Then, the detergent with water is extracted by a small water pump then ejected from the spray pipe connecting to the scraper link as shown in Fig. 2. The water flow can be regulated manually through the valve on the water inlet pipe. Finally, the brush is driven by two timing belts connected to a DC motor. It should be noted that the rotation direction is clockwise in the perspective of Fig.2. On one hand, with this rotating direction, a relative motion between the brush and the window can be achieved when cleaning work happens from top to bottom. On the other hand, the water can be thrown to the recycled water box of the cleaning unit and then taken away to the sink. The water recycle capacity in the cleaning unit makes the whole system lighter and environmentally friendly by saving water and filtering the contamination.

The *IACM* can not only save the control degree of freedom and guarantee the full contact with the cleaning surface, but also create a water recycle system to make the whole system lighter and easier to be set on any other kinds of high-rises locomotion system.

III. Task-oriented Impedance Control for *IACM*

A. Dirt Removal Model

Even though the cleaning Since the dirt on the window cannot be removed through one time operation, the removal rate of the surface dirt should be quantified with the related influence factors. The dirt removal rate model [1] here is:

$$\Delta S = \int_0^t \boldsymbol{k}_{\mathrm{p}} \boldsymbol{v} \boldsymbol{p} \mathrm{d}t, \tag{1}$$

where, S is the dirt coverage; ΔS is the dirt removal rate; $\boldsymbol{p}$ is the pressure to the surface; $\boldsymbol{v}$ is the cleaning rate; t is the time; $\boldsymbol{k}_{\mathrm{p}}$ is the cleaning constant, it differs from the cleaning surface and dirt type. The pressure of the surface is directly related to the force and the touching surface area, with the fully touching of the cleaning unit, the pressure can be simplified as the force from the manipulator. The cleaning velocity is the combination of the robotic arm end-effector movement and the rotating velocity of the brusher motor. Comparing with the rotating velocity, the robotic arm end-effector movement velocity is quite small, besides. The brusher and the rotating motor, which is combined as the brushing subsystem, accounts for a large proportion in the whole weight of the cleaning unit, the velocity fluctuation of the brushing subsystem gives a quite large burden to the robotic arm, since a little inertia acceleration at the tip causes a quite large torque to the base joint. Thus, the velocity of the brusher motor here, keeps in constant. Then, the dirt removal model can be written as:

$$\ddot{S} = \boldsymbol{k}_{\mathrm{s}} \boldsymbol{F}, \tag{2}$$

where, k_{s} is the removal constant, it depends on the velocity, surface condition, cleaning surface and the dirt type factors. Under no previous knowledge of the dirt type, for the dirt removal task, we should design better F to result in $s \to 0$ as soon as possible.

B. Impedance Model

Interaction directly influences the dirt removal results, impedance control has been proposed as an effective method for tracking a reference trajectory and meanwhile keeping the interaction relations between the manipulator and the operation surface.

The impedance model is used to model the virtual effects when the manipulator interacting with the external environment, which tells us that the control result of the manipulator will be just like a mass-damper-spring system, so that the interaction force can be quickly converged. The model can be written as [16]:

$$\boldsymbol{M}_d(\ddot{\boldsymbol{X}} - \ddot{\boldsymbol{X}}_d) + \boldsymbol{C}_d(\dot{\boldsymbol{X}} - \dot{\boldsymbol{X}}_d) + \boldsymbol{K}_d(\boldsymbol{X} - \boldsymbol{X}_d) = \boldsymbol{\tau}_e \ .$$

The overall model of the IACM consists of three subsystems, i.e. the robot, the impedance model and the dirt removal model, as follows:

$$\ddot{S} = \boldsymbol{k}_{\mathrm{s}} \boldsymbol{F}, \tag{3}$$

$$\boldsymbol{M}_d(\ddot{\boldsymbol{q}} - \ddot{\boldsymbol{q}}_d) + \boldsymbol{C}_d(\dot{\boldsymbol{q}} - \dot{\boldsymbol{q}}_d) + \boldsymbol{K}_d(\boldsymbol{q} - \boldsymbol{q}_d) = \boldsymbol{\tau}_e, \tag{4}$$

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{D}\dot{\boldsymbol{q}} + \boldsymbol{G} = \boldsymbol{\tau} + \boldsymbol{\tau}_e, \tag{5}$$

where $\boldsymbol{q} = [q_1, \cdots, q_n]^T \in \Re^n$ is the vector of robot configuration, q_i $(i = 1, \cdots, n)$ is the configuration of the i^{th} joint, $\boldsymbol{M} = \mathrm{diag}(M_1, \cdots, M_n) \in \Re^{n \times n}$ is the diagonal mass matrix of the robot where M_i are positive constants, $\boldsymbol{D} = \mathrm{diag}(D_1, \cdots, D_n) \in \Re^{n \times n}$ denotes the diagonal friction matrix where D_i is also positive constants, $\boldsymbol{G} \in \Re^n$ is the gravity matrix; and $\boldsymbol{q}_d$ is the desired joint angles, while $\boldsymbol{M}_d; \boldsymbol{C}_d; \boldsymbol{K}_d \in \mathcal{R}^{n*n}$ denote the desired inertia, the desired damping, the desired stiffness matrices respectively, which are diagonal and positive definite. $\boldsymbol{\tau}_e$ is the interaction torque between the surface and the manipulator head, while $\boldsymbol{\tau}$ is the control input for the robotic arm. This system has a clear feature for back-stepping control algorithm, which means that the stability of each subsystem makes sure the convergence of the whole system.

C. Control Algorithm

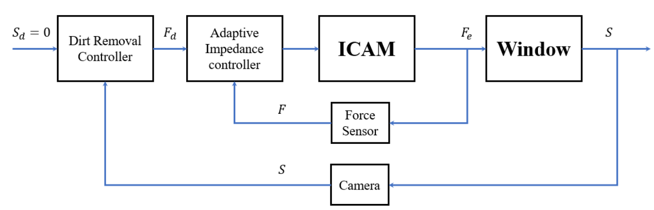

Fig. 3. Controller structure diagram of *IACM*.

Algorithm 1: Task-oriented Impedance Control Algorithm

Input: cleaning trajectory $\boldsymbol{X}_d$
Output: dirt coverage $S \to 0$
detect init dirt coverage S_0;
$S = S_0$;
while $S > S_{threshold}$ **do**
  $\boldsymbol{X} = kinematic(\boldsymbol{q})$;
  if $\boldsymbol{X} \neq \boldsymbol{X}_d$ **then**
    $\boldsymbol{F}_d$ = DirtRemovalController(S);
    $\boldsymbol{V}_1$ = ImpedanceController($\boldsymbol{q}$,$\boldsymbol{F}_d$);
    $\boldsymbol{V}_2$ = trajectoryVelocityController($\boldsymbol{X}_d$, $\boldsymbol{X}$);
    $\dot{\boldsymbol{q}}_d = \boldsymbol{J}^{-1} * (\boldsymbol{V}_1 + \boldsymbol{V}_2)$
  end
  detect init dirt coverage S;
end

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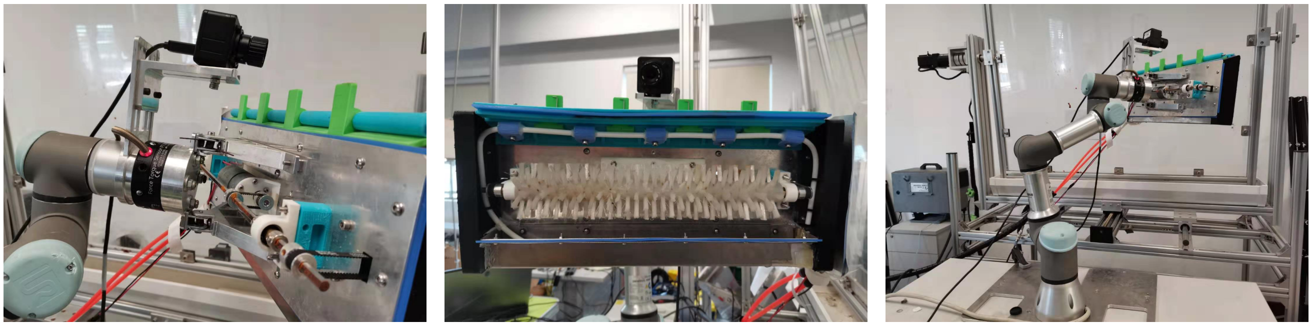
[1] This model comes from the Preston equation [15], which is a general model for measuring the removal rate of the processed surface in the mechanical machining area.



(a) (b) (c)

Fig. 4. Experiment Setup of the Integrated Autonomous Cleaning Manipulator.

The control scheme of the task-oriented impedance control algorithm can be seen in table 12 and Fig. 3. Three controllers are needed for the whole control scheme. The input is the dirt coverage, which means that the manipulator will start work while dirt is detected. The through the impedance controller and the trajectory velocity controller, a desired end effector velocity $\boldsymbol{X}_d$ is calculated, then through the inverse kinematics, joint velocity can be got and set.

From eq. 3, the convergence of the system is guaranteed, while the adjustment should be made to achieve a less power and high cleaning effects. Since from the equation aspect, the following can be got :

$$S = 1/(\boldsymbol{K}_s * \boldsymbol{F})^2 * exp(\boldsymbol{K}_s * \boldsymbol{F} * t)$$

which gives us the hint that the fastest convergence of the dirt removal is in exponential, which reminds us the sliding control can make the system converge to the equilibrium exponentially. Actually, as an optimal problem, the verification can be seen in [17]. Introducing the sliding vector:

$$\dot{\boldsymbol{s}} = \dot{\boldsymbol{F}} - \dot{\boldsymbol{F}}_r = \dot{\boldsymbol{F}} - \dot{\boldsymbol{F}}_d + \alpha_s * \Delta \boldsymbol{F} \tag{6}$$

where α_s is positive constants. The following controller can be proposed:

$$\boldsymbol{u}_s = -\boldsymbol{K}_s \boldsymbol{s} - k_q \Delta \boldsymbol{F}, \tag{7}$$

where $\boldsymbol{K}_s$ and k_q are positive scalars.

As to the impedance model control, it is a simple mass-damper-spring system, assume the $\boldsymbol{M}_d, \boldsymbol{C}_d, \boldsymbol{K}_d$ is predefined, the system is a normal 2-order system, PID control is used here to adjust the relationship between the velocity and the F_d defined in eq. 7. The convergence of the PID for this kind of system has been verified in [18] and [19].

IV. Experiment

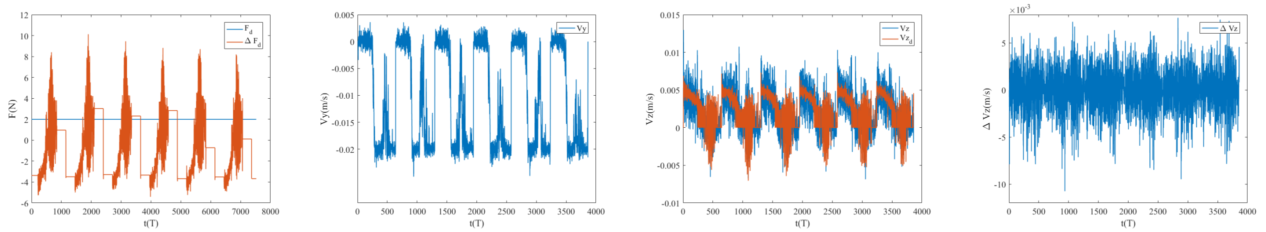
An experimental setup of *IACM* has been established in The Chinese University of Hong Kong, shown in Fig. 4, is made up with a Universal Robot 3; an industry camera is installed on the end effector, and it is 2.1 million pixels and 15FPS; the force sensor here is the Robotiq FT-300 force sensor; a brush motor here is a 12 Voltage DC motor; the motor, the sewage pump and clean water pump are connected with Arduino Mega 2560, and controlled by the laptop through wireless. The hardwares are connected to a laptop with Unbuntu16.04, and running Robot Operation System(ROS kinetic).

To verify the effectiveness of the proposed control scheme, the proposed task-oriented impedance control is compared with the common used constant impedance control algorithm with two different impedance constant forces. The dirt coverage detection algorithm here is that we utilize the saturation of the color pictures from HSV space, choose a suitable threshold of 63 for deciding higher values as dirt. The denoising method for force sensor is the balance filter, with factor as 0.95.

To verify the real cleaning effects, a test window platform is also set up in the lab, which can be seen in Fig. 4(c), the window installed in the platform can be adjusted by the horizontal linear stage and the rotating stepping motor to fix the position and angle of the window. In the whole experiments, the dirt used here is the tomato sauce, which is not so easy to clean when it solidifies, so that more times are needed to clean the dirt; besides, here the force threshold of F_d is very small to reflect the phenomenon that when the dirt is not easy to remove, what's the performance of the proposed control scheme. Another thing should be notified that in the control algorithm in previous section, a trajectory controller is applied to control the trajectory of the cleaning unit brush. Here, to simplified, since the window we set here is in static, the trajectory here is simplified as a 0.22 m line from up to down, while the velocity along the line is give as 0.02m/s, which means that in 12, $\boldsymbol{V}_2 = [0, 0.02m/s, 0, 0, 0, 0]$.

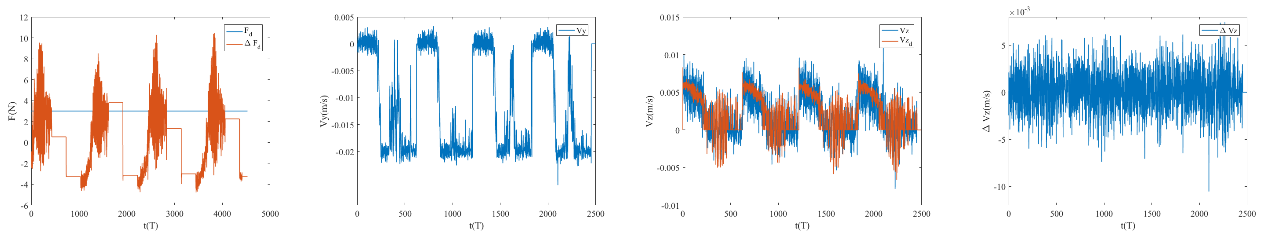
A. Constant Impedance Control of IACM Cleaning

For the constant impedance control, which means that no feedback from the camera dirt coverage information is used. However, for the convergence of the desired F_d, PID controller for impedance control is still used here, and the gains are $K_p = 1/1291; K_i = 4.1 * 10^{-9}; K_d = 3 * 10^{-4}$. Experiment results of constant desired interaction force of 2N and 3N are shown in Fig. 5 and Fig. 6, respectively. From the figures, for less force, more cleaning times are needed. The constant 2N experiment needs 6 loops, while 3N only needs 4 loops.



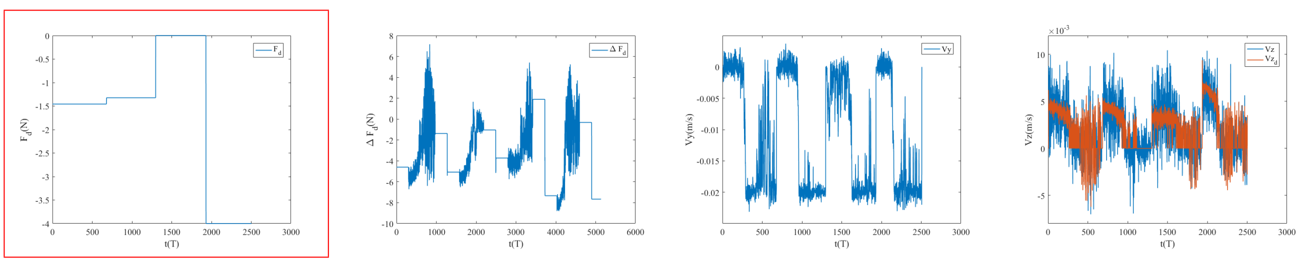
(a) Desired impedance force F_d and the force errors ΔF (b) y axis real velocity of the end-effector (c) z axis real velocity of the end-effector (d) z axis velocity errors of the end-effector

Fig. 5. Experiment results of constant impedance force of 2N.



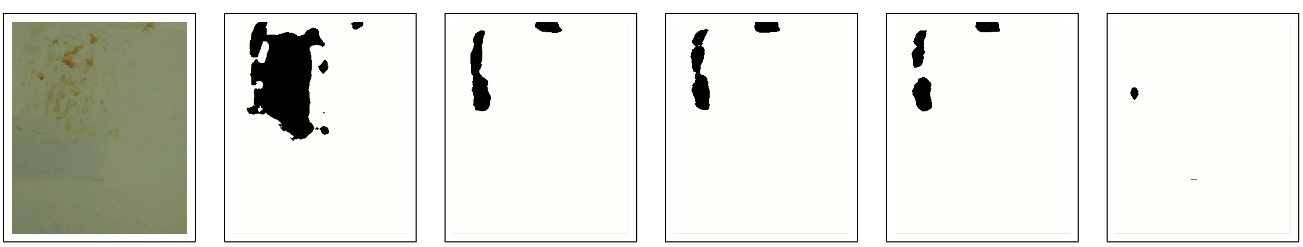
(a) Desired impedance force F_d and the force errors ΔF (b) y axis real velocity of the end-effector (c) z axis real velocity of the end-effector (d) z axis velocity errors of the end-effector

Fig. 6. Experiment results of constant impedance force of 3N.



(a) Desired impedance force F_d (b) impedance force errors of the end-effector (c) y axis real velocity of the end-effector (d) z axis real velocity of the end-effector

Fig. 7. Experiment results of impedance control.



(a) (b) (c) (d) (e) (f)

Fig. 8. Dirt detection results at the start of every loop. The detected coverages are: 0.1576, 0.0336, 0.0333, 0.0305, 0.0012

B. *Task-oriented Impedance Control of IACM Cleaning*

Experimental results of task-oriented impedance control of *IACM* Cleaning are decipted in Fig. 7. From Fig. 7(a) with red box outlines, we can find that the adjustment of the force has worked. Analysing the curve, and comparing it with the dirt detection results, shown in Fig. 8, following items are contributed to the whole cleaning system. Firstly, when the dirt is moderate, the force is only about 1.5 N, which is less than the constant value results. However, when the dirt decreases to a value, the dirt removal rate becomes very low, no matter the desired force is set to 3N, or 1.6N. If that's the case, for constant 3N impedance work, shown in Fig. 8(a) , the constant force makes no changing, even though in the next step, no obvious dirt is removed. However, the task-oriented impedance control increases the force possibility of the cleaning.

Even though the initial dirt of every experiments are not same, clearly results from Fig. 8(a) show that the first round of cleaning makes the dirt quickly goes down to 0.15, no matter how much force you applied to the window. This also tells us the necessarity of changing the impedance force during the cleaning process if high cleaning quality should be reached when you don't have a precise cleaning normal force calibration in advance. From the aspect of time consumption, from Fig. 8(a), to reach the cleaning requirements, here we set 0.002, the constant 2N experiment needs 6 loops, while 3N and our proposed method only needs 4 loops, which clearly decrease the time consumption.

The energy consumption of the two experiments can be compared through the force during the whole process, since the cleaning motor rotates in the same constant speed, while the consumption of the robotic arm can be reflected by the impedance force. Comparing the force of the two experiments, specially for 3N and the task-oriented control, surely the task-oriented impedance control costs less, since the force of every loop are 1.5N, 1.2N, 0N and 4N, while for four loops of 3N experiment, it is always 3N. Clearly, it consumes less.

In a word, comparing with the 3N force results, the proposed method is energy saving, while comparing with the 2N force results, it has good efficiency.

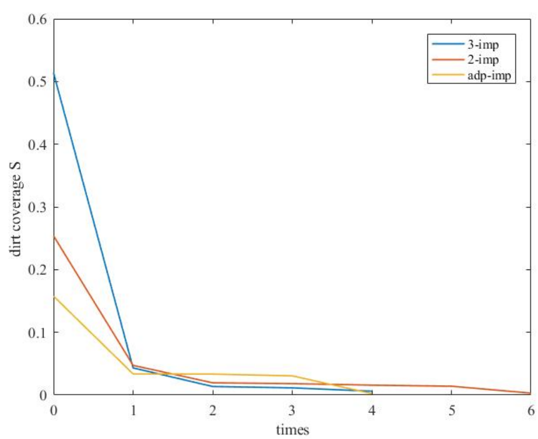


Fig. 9. Dirt removal results of every loops for experiments of constant impedance force 3N, 2N and the task-oriented impedance force. The initial coverages are: 0.5138,0.2539,0.1576

V. Conclusion

An integrated autonomous cleaning manipulator has been designed in this paper, and for a better control performance for dirt removal, a task-oriented impedance control algorithm has been proposed. The mechanical design of the *IACM* not only fulfills the whole steps of the manual cleaning surface, guarantees the cleaning effects of the system but also by adding a water recycling system in it makes the system simpler, lighter and more environmentally friendly. The proposed control algorithm comes from the important energy and efficient problems of the high-rise autonomous system, through using the feedback of the dirt removal model and impedance model, it connects the relationship of the dirt to manipulator joint control, which can be extended to other surface machining areas. The experimental results of the comparison of the constant interaction force and the task-oriented interaction force show that compared with the higher force results, it is energy-saving, while comparing with the lower force results, it has good efficiency. Future work will focus on how to solve the vibration problem when the environment condition is unknown.

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