연구논문

Journal of Drive and Control, Vol.14 No.3 pp.25-31 Sep. 2017
ISSN(print) 2234-8328 ISSN(online) 2287-6146
http://dx.doi.org/10.7839/ksfc.2017.14.3.025

Unified Approach for Force/Position Control in the Vehicle Body Sanding Process

Chi Thanh Nguyen[1], Jae Woo Lee[2] and Soon Yong Yang[3]*

Received: 22 Mar. 2017, Accepted: 27 Jul. 2017

Key Words : Cartesian Robot, Surface Processing, Unified Approach, Transient Process, Interaction Force.

Abstract: This study presents a methodology for simulating a unified approach that controls interaction force between tool and objective by using a synthesis method of robot interacting control law for stabilizing the transient process of motion. Root locus is used to analyze stabilization of motion deviation characteristics. Based on responses of motion deviation, contact force is derived to satisfy exponential stability and we generate control input with respect to motion trajectories and interaction force. Moreover, simulation is applied to experimental application of a Cartesian robot driven by two stepper motors, and the noise of feedback signals is considered as presence of system inaccuracies, and the unified approach of interaction force control is examined precisely.

Nomenclature

x, x_p : real and programmed motion along a x-axis
y, y_p : real and programmed motion along a y-axis
θ_1, θ_2 : the angles of joint 1 and joint 2
η_x, η_y: motion deviations along x, y-axis.
μ_x, μ_y: interaction force deviations along x, y-axis
τ_x : motor torque control input for x-axis actuator, Nm
τ_y : motor torque control input for y-axis actuator, Nm
F_x : x-axis complement force, N
F_y : y-axis contact force, N
Φ: slope angle of flat plane.
M: constant matrix of inertia.
L_h: constant matrix of viscous friction.
L_k: constant matrix of stiffness.
m_e: the equivalent mass of environment inertia.

* Corresponding author: soonyy@ulsan.ac.kr
1 Department of Mechanical and Automotive Engineering, University of Ulsan, Ulsan 44610, Korea
2 Department of Smart Robot and Automation, Woosong College, Daejeon 34606, Korea
3 Department of Mechanical Engineering, University of Ulsan, Ulsan 44610, Korea

1. Introduction

The objective of research is to study on the control method of constant contact force when robot works on arbitrary trajectories along vehicle body surface.

Recently, manipulators are used widely in the surface processing tasks as sanding, grinding, deburring, polishing industry because of its benefits such as the improvement of the quality of surface performance. They automatically travel on a target route to make the products having the same quality. In order to improve the vehicle body surface performance or to prevent overloading or damage to the tool during operation, the actuation force needs to be controlled with predefined values. In general these operations need to be controlled simultaneously both of the tool trajectory and interaction force.

In force/position control system, a closed-loop controller is used to control interaction force and robot trajectories along vehicle body surface. The challenge in this algorithm is how to change the position, velocity

Fig. 1 Vehicle body sanding in the industry (internet).

and acceleration for maintaining the predefined interaction force. This approach combines two independent subtasks in Cartesian coordinate frame, in which one subtask is the robot's motion control along a predetermined trajectories and the other is the control of the interaction force of the robot and objectives.

In the previous research, the hybrid position/force control approach [1, 2] is based on compliant control algorithm and applies two independent control loops for a 2 DOF compliant joint manipulator. The two orthogonal axis mechanism system is used to implement the interaction control approach [3], this approach divides the control algorithm into two independent subtasks, which are motion control along horizontal axis and the control of interaction force between tool and work-piece along the y-axis. The motion and interaction force of robot are estimated by the quality of the pre-set transient processes. To improve the performance of force/position control, this paper studies a unified approach and its advantages on controlling the contact force for scalar robot model. The approach of dynamic interaction control defines two control subtasks responsible for the stabilization of robot position and interaction force. Both control subtasks utilize dynamic model of the robot and the environment in order to ensure the tracking of both the nominal motion and force.

The unified control law stabilizes simultaneously both the tool motion and interaction force. This method applies the exponential stability for closed-loop system and maintains the programmed quality of transient processes of motion and interaction force.

This paper is organized as follows, in section 2, we described the unified force/position control law for Cartesian robot to ensure the interaction force when robot works on known trajectories along with work-piece surface. This section includes modeling of robot dynamics and objective surface dynamics in subsection 1, and the transient processes of robot motion and interaction force in subsection 2. Section 3 shows the simulation implementation for such unified approach. The final is the conclusion of this research and forward direction of experimental application.

2. Unified Force/Position Control for Cartesian Robot

In the automotive industry, the modern robots widely are used to process the vehicle body components, the high quality requirements are standardized with the acceptable ratio. For such purpose, the study presents a Cartesian robot model for sanding vehicle body, the simulation mode is supposed that the robot works on the horizontal XY plane, moves the tool over flat objective which rotates about horizontal axis with variant angle φ.

In general, the control law is synthesized by stabilizing the robot motion and interaction force simultaneously. The control law possesses exponential stability of closed-loop systems and ensures the preset quality of transient processes of motion and interaction force. This section uses the exponential stability theorem [4] for both motion and contact force. For adapting such stability, the initial conditions and transient processes of motion and interaction force need to be set to correspond with control laws. The control law, derived from dynamic modeling and stabilizing synthesis of transient processes, is applied for the robot closed-loop dynamic model, shown as:

$$\tau = H(q)\left[\ddot{q}_p + P(\eta,\dot{\eta})\right] + h(q,\dot{q}) - J^T(q)F \tag{1}$$

2.1 Dynamic Modeling

The dynamic model of the robot interacting with its work-piece:

$$H(q)\ddot{q} + h(q,\dot{q}) = \tau + J^T(q)F \tag{2}$$

The model of object dynamics:

$$M(q)\ddot{q} + L(q,\dot{q}) = S^T(q)F \tag{3}$$

Where $q=[\theta_1\theta_2]^T$ is angular position vector of the robot.

In this content, the operational space approach [5] was used, the end-effector equations of motion can be written in the Cartesian coordinate frame. The dynamic models are transformed to Cartesian coordinate frame:

$$\Lambda(z)\ddot{z}+\nu(z,\dot{z})=T+F \tag{4}$$

$$\mathcal{M}(z)\ddot{z}+\mathcal{L}(z,\dot{z})=-F \tag{5}$$

Where the Cartesian coordinate $z=[x\ \ y]^T=\chi(q)$, the position coordinate are induced from angle vector.

The matrices $M(q)$ and $L(q,\dot{q})$ are constant matrices of inertia, viscous friction and stiffness, respectively.

Assuming that all the functions in (2), (3), (4) and (5) are continuously differentiable with respect to all variables with initial conditions $z(t_0)=z_0$ and , $\dot{z}(t_0)=\dot{z}_0$ and the programmed motion $z_p(t)$ and programmed interaction force $F_p(t)$ satisfy environment dynamic model (5), so the control objective is to achieve: $(z(t),\dot{z}(t),F(t))\rightarrow(z_p(t),\dot{z}_p(t),F_p(t))$ when $t\rightarrow\infty$. These responses of system are specified by the transient process synthesis.

2.2 Transient processes of motion and force

The transient processes of motion and contact force generally are determined by the equations:

$$\ddot{\eta}=P(\eta,\dot{\eta}) \tag{6}$$

$$\ddot{\mu}=Q(\mu,\dot{\mu}) \tag{7}$$

Where $\eta(t)=z(t)-z_p(t)$, $\mu(t)=F(t)-F_p(t)$, the *P* and *Q* are continuous functions and they are used to determine characteristics of the transient processes for stabilizing the motion and interaction force.

The P is the function of vectors η and $\dot{\eta}$ with Γ_1 and Γ_2, where Γ_1 and Γ_2 are constant coefficient matrices, the (6) can be rewritten as:

$$\ddot{\eta}=\Gamma_1\dot{\eta}+\Gamma_2\eta \tag{8}$$

As for two-link revolute robot, the environment dynamics are depicted as:

$$F_y=(m+m_e)\ddot{y}+h_y\dot{y}-k_y y \tag{9}$$

$$F_x=m\ddot{x}+h_x\dot{x}+\nu_x(F_y-m_e\ddot{y})sign(\dot{x}) \tag{10}$$

The deviations of environment dynamics for positive velocity:

$$\mu_y=(m+m_e)\ddot{\eta}_y+h_y\dot{\eta}_y-k_y\eta_y \tag{11}$$

$$\mu_x=m\ddot{\eta}_x+h_x\dot{\eta}_x+\nu_x(\mu_y-m_e\ddot{\eta}_y) \tag{12}$$

We assume that the constant matrices of inertia, viscous friction and stiffness matrices are: $M=\begin{bmatrix} m & \nu_x m \\ 0 & m+m_e\end{bmatrix}$; $L_h=\begin{bmatrix} h_x & \nu_x h_y \\ 0 & h_y\end{bmatrix}$; and $L_k=\begin{bmatrix} 0 & -\nu_x k_y \\ 0 & -k_y\end{bmatrix}$, respectively.

So the correspondence between motion deviation and force deviation can be expressed:

$$\mu=M\ddot{\eta}+L_h\dot{\eta}+L_k\eta \tag{13}$$

To get the transient process of interaction force, the approximation is applied for linearized system with definitions $w=[\eta\ \ \dot{\eta}]^T$, $u=[\mu\ \ \dot{\mu}]^T$, $\Gamma=[\Gamma_1\ \ \Gamma_2]$ and $L=[L_k\ \ L_h]$. So, the equations (8) and (13) can be rewritten as:

$$\dot{w}=\begin{bmatrix} 0 & I \\ \Gamma_2 & \Gamma_1\end{bmatrix}w=\Gamma_\eta w \tag{14}$$

$$\mu=(M\Gamma+L)w=Cw \tag{15}$$

We obtain:

$$u=\begin{bmatrix} C \\ C\Gamma_\eta\end{bmatrix}w=\alpha w \tag{16}$$

Where $\alpha=\begin{bmatrix} M\Gamma_2+L_k & M\Gamma_1+L_h \\ (M\Gamma_1+L_h)\Gamma_2 & (M\Gamma_1+L_h)\Gamma_1+M\Gamma_2+L_k\end{bmatrix}$, assume that the matrix α is nonsingular, deriving from (14) and (16) we obtain $\dot{u}=Q_\mu u$ where $Q_\mu=\alpha\Gamma_\eta\alpha^{-1}$. So the transient process of contact force can be obtained:

$$\ddot{\mu}=Q_1\dot{\mu}+Q_2\mu \tag{17}$$

Where $[Q_2 \quad Q_1] = [\alpha_2 \quad \beta_2]\alpha^{-1}$, $\alpha = \begin{bmatrix} \alpha_0 & \beta_0 \\ \alpha_1 & \beta_1 \end{bmatrix}$, $\alpha_0 = L_k + M\Gamma_2$, $\beta_0 = L_h + M\Gamma_1$, $\alpha_{i+1} = \beta_i \Gamma_2$, $\beta_{i+1} = \alpha_i + \beta_i \Gamma_1, i = 0,1$. So the coefficients of function Q are approximated from the coefficients of the function P.

When $(\ddot{\eta}, \dot{\eta}, \eta) \rightarrow 0$ as $t \rightarrow \infty$, (11) and (12) can induce $(\ddot{\mu}, \dot{\mu}, \mu) \rightarrow 0$.

3. Simulation

3.1 Simulation Setup

As mentioned in previous section, the Cartesian robot are described as Fig. 2 and parameter table 1. The robot consists of two revolute links on the plane and a flexible movement tool is mounted on the tip.

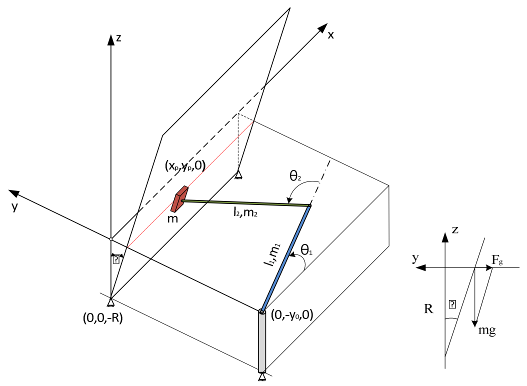

Fig. 2 Model of Cartesian robot in the process.

Table 1 simulation parameters

Desired contact force (F^0)	100 [N]
Horizontal velocity (V_0)	80 [mm/s]
Mass of tool (m)	5 [kg]
Mass of link 1 (m_1)	10 [kg]
Mass of link 2 (m_2)	7 [kg]
Length of link 1 (l_1)	1 [m]
Length of link 2 (l_2)	1 [m]
Vertical distance of flat plane (R)	0.3 [m]
Robot foot in y-axis (y_0)	1.4 [m]

The dynamics modeling of the Cartesian robot is depicted by the positive matrices of inertia moment, nonlinear functions of centrifugal, Coriolis' and gravitational moment and Jacobian matrix. All of these coefficients are induced by the angular position vector of robot.

The relation between $z = [x \ \ y]^T$ and $q = [\theta_1 \theta_2]^T$ is:

$$z = \chi(q) = \begin{bmatrix} cos(\theta_1) + cos\,(\theta_1 + \theta_2) \\ sin(\theta_1) + sin(\theta_1 + \theta_2) - 1.4 \end{bmatrix} \tag{18}$$

The contact force vector is introduced in Cartesian space $F = [F_x F_y]^T$, in which the contact force F_y is a sum of the inertial, frictional and gravitational components:

$$F_y = 7.45\ddot{y} + 0.1\dot{y} - 163.5y \tag{19}$$

Where $k_y = \dfrac{mg}{R} = 163.5$ is environment stiffness coefficient, $m_e = \dfrac{mR}{y_p} = 2.45$ and is the support equivalent mass.

The horizontal component of contact force is a sum of the inertial and frictional forces:

$$F_x = 5\ddot{x} + 0.1\dot{x} + 0.01(F_y - 2.45\ddot{y})sign(\dot{x}) \tag{20}$$

The equations (19) and (20) are reformed from environment dynamics equation (5). For maintaining the constant contact force, the programmed contact force along the y-axis is set as constant.

$$F_{y_p}(t) = F_y^0 = F^0 = 100 \text{ (N)}$$

And the nominal motion along the x-axis:

$$x_p(t) = x^0(t) = V_0 t, V_0 = 0.08 \text{(m/s)}$$

From (15), (16) we can determine the horizontal component of contact force F_x and vertical motion y_p:

$$F_{x_p}(t) = F_x^0(t) = h_x V_0 + \nu_x F^0 = 1.008 \text{(N)}.$$

And $y_p(t) = y^0(t) = -\frac{1}{k_y} F^0 = -0.61 \text{(m)}$.

3.2 Procedure Proposal

In order to implement the unified approach for synthesizing the force/position control law, the contact force, which acts on the dynamic vehicle body, is studied through the characteristics of the transient process. This process is induced by the sanding tool motion's transient process as mentioned in section 2.1. The problem needs to be solved that is to find out the good form of the transient process of motion, that satisfies the exponential stability condition, so the function P in the equation (6) is investigated by being supposed as below:

$$\ddot{\eta}_x + 2\zeta_x\omega_x\dot{\eta}_x + \omega_x^2\eta_x = 0 \tag{21}$$

$$\ddot{\eta}_y + 2\zeta_y\omega_y\dot{\eta}_y + \omega_y^2\eta_y = 0 \tag{22}$$

In which, η_x, η_y are motion deviation between the real motion and programmed motion along x-axis, y-axis respectively. For generating the acceptable control model of the transient models in (21, 22), the motion transient processes are analyzed in the s-space by using the Laplace transformation method.

From the equation (21), the Laplace transform of motion deviations can be rewritten as equation (23) with foreknown initial conditions, the same case for y-axis motion in the equation (22).

$$H(s) = \frac{0.05s + 0.1\zeta_x\omega_x}{s^2 + 2\zeta_x\omega_x s + \omega_x^2} \tag{23}$$

So the system has two poles and one zero, the trivial solution of zero is $s_0 = -2\zeta_x\omega_x$ and solutions of poles are $s_{1,2} = -\zeta_x\omega_x \pm \omega_x\sqrt{\zeta\frac{2}{x} - 1}$ respectively. The problem is considered as a simple second-order system. The root locus method is used to analyze the basic characteristics of transient response of a closed-loop system is closely related to location of poles in the s-plane. When the poles in the left of the s-plane the system response increases, similarly when the poles on the imaginary axis and in the right of s-plane the system response is neutral and increases respectively. For linear system, the stability is related to the location of the roots of the characteristic equation. As the equation (23), the damping and undamped natural frequency varies the locations the system's poles are changed respectively.

Through analyzing the characteristics of transient process in root locus procedure, the rising time and delay time are proportional to damping ratio and inversely proportional to natural frequency. And based on the requirement of the transient time and damped state of system, the damping ratio and natural frequency can be tuned to generate the acceptable control model of the programmed interaction force with fast responses of step servo motors. In this case, the closed-loop root locus of such controller with $\zeta = 0.9$, $\omega = 8$ is examined as in Fig. 3. And the transient processes' responses are shown in Fig. 4 with the acceptable specifications are expressed on table 2.

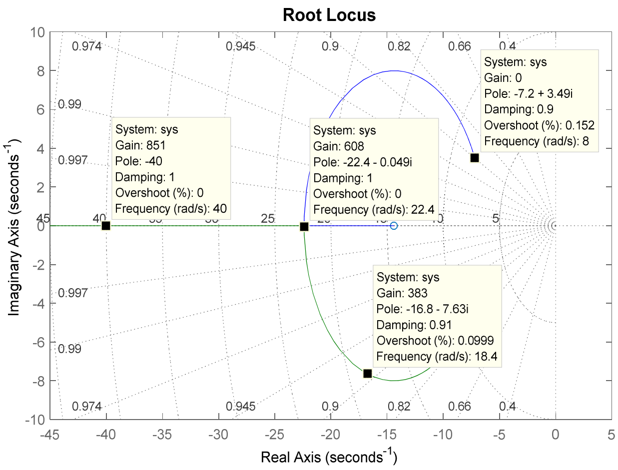

Fig. 3 Root Locus

Table 2 Specifications of transient process

Rising time (t_r)	365 [milliseconds]
Delay time (t_d)	200 [milliseconds]
Steady state error	2.926e-64 [m]

3.3 Results and Discussions

Based on the above root locus analysis, we can do tuning the damping ratio and frequency to get the acceptable responses for desired interaction control design.

Where $\ddot{\eta} + 14.4\dot{\eta}_x + 64\eta_x = 0$ and $\ddot{\eta}_y + 14.4\dot{\eta}_y + 64\eta_y = 0$. The responses of motion and interaction force are shown as the following figures.

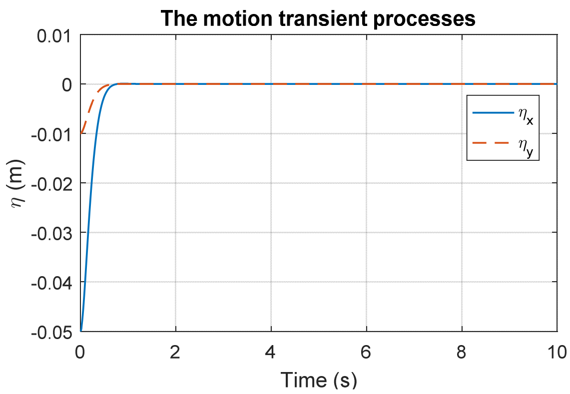

Fig. 4 The motion transient processes

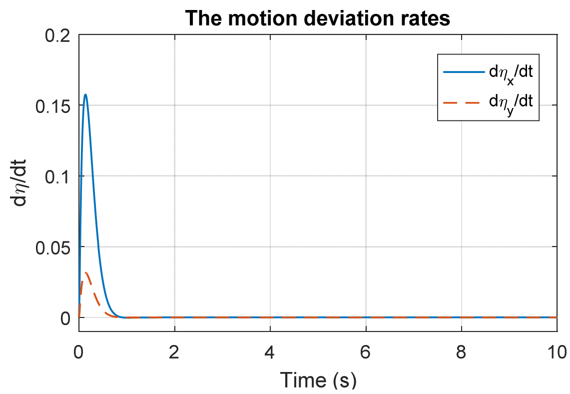

Fig. 5 The motion deviation rates.

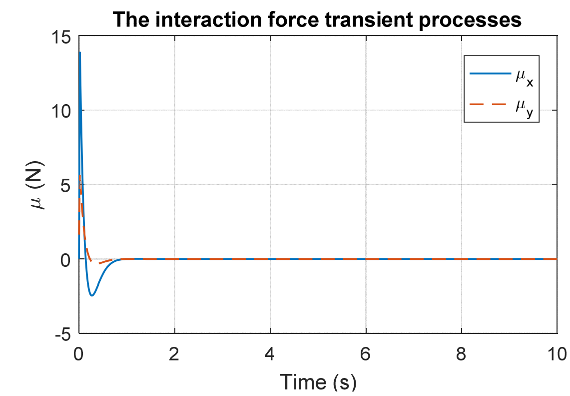

Fig. 6 The interaction force transient processes.

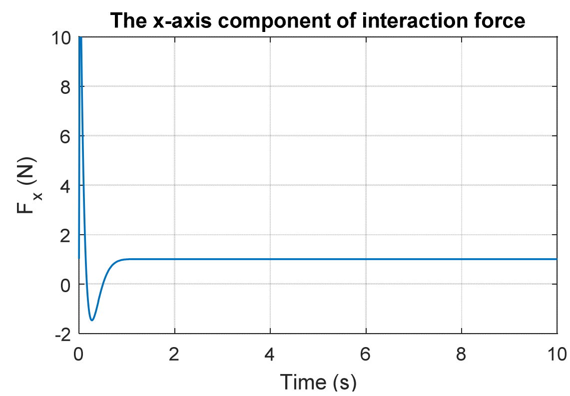

Fig. 7 The x-axis component of interaction force.

In this proposal, the sanding motion is estimated with foreseen trajectory. In which the desired horizontal velocity is proposed 80 mm/s along x-axis and the y direction desired positon are constant depending on the desired interaction force.

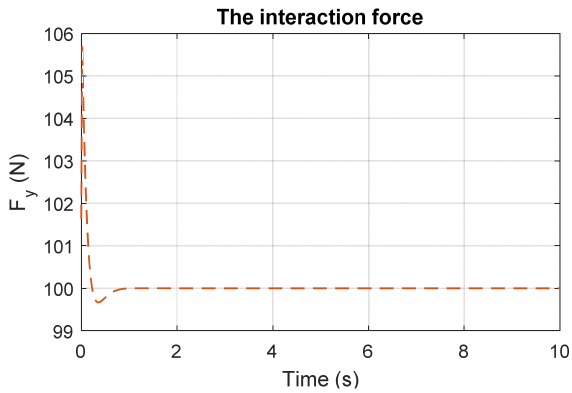

Fig. 8 The interaction force.

When such transient processes are applied, the response of interaction force reached the steady state adaptively. For adapting above responses, the joints' revolutions are estimated by using robotic invert kinematic as shown in Fig. 9, and 10.

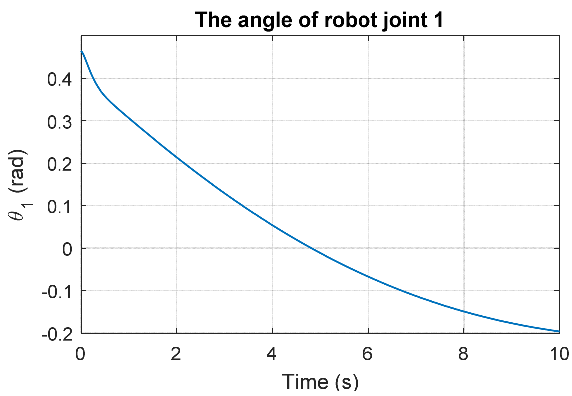

Fig. 9 The angle of robot joint 1.

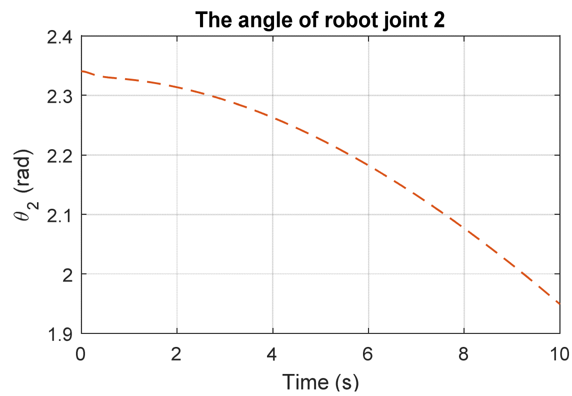

Fig. 10 The angle of manipulator joint 2.

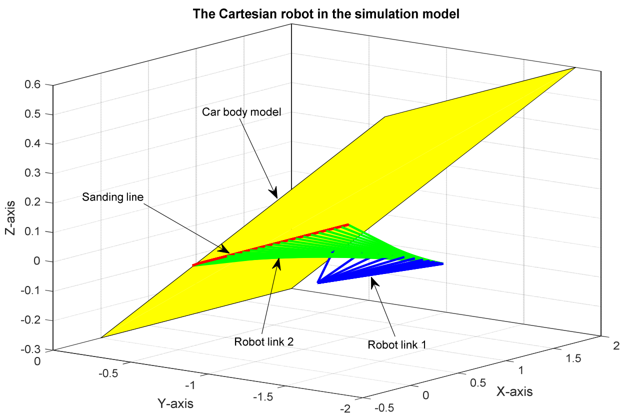

Fig. 11 The estimation of Cartesian robot.

The estimation of Cartesian robot is shown as Fig. 11 based on the simulation data. The slope angle φ is calculated as -1.1148 rad, about -63.872 degree.

4. Conclusion

This study describes the unified approach, which was developed from hybrid force/position control method. This approach combines the task of stabilizing both the robot motion and interaction force simultaneously in Cartesian space. In which, the transient processes of contact forces are derived through the proposed transient processes of motion and environment dynamics. This one-to-one correspondence between the interaction response and motion regulation is obtained and this approach ensures the exponential stability of system through synthesis of motion and force transient processes.

The unsettled environment dynamics equation was assumed to be linear in Cartesian space so that the obtained results are applicable to nonlinear environment dynamics in the range of validity of the linear approximation.

References

1) M. H. Raibert and J. J. Craig, "Hybrid Position/Force Control of Manipulators", Trans. ASME J. of Dynamic System, Measurement and Control Vol. 103, No. 2, pp. 126-133, 1981.
2) M. T. Mason, "Compliance and Force Control for Computer Controlled Manipulators", IEEE Trans. on Systems, Man, and Cybernetics, Vol. SMC-11, No. 6, pp. 418-432, 1981.
3) C. T. Nguyen, J. W. Lee, S. Y. Yang, "A study on Interaction Control of Force and Motion between Tool and Workpiece", Proceedings of Autumn Conference on Drive and Control, pp. 157-161, 2016.
4) V. C. Aitken, H. M. Schwartz, "On the Exponential Stability of Discrete-Time System with Applications in Observer Design", IEEE Trans. on Automatic Control, Vol. 39, No. 9, pp. 1959-1962, 1994.
5) O. Kathib, "A Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation", IEEE J. of R&A, Vol. RA-3, No. 1, 1987.
6) F. Aghili, J-C. Piedboeæuf, "Emulation of Robots Interacting with Environment", IEEE/ASME Transactions on Mechatronics, Vol. 11, No. 1, pp. 35-46, Feb 2006.
7) M. Stepien, et al, "Control of Tool/Workpiece Contact Force with Application to Robotic Deburring", IEEE Journal of Robotics and Automation, Vol. RA-3, N0.1, pp. 7-18, Feb 1987.
8) S. Jung, T. C. Hsia, "Adaptive Force Tracking Impedance Control of Robot for Cutting Nohomogeneous Workpiece", IEEE Int' Conference on Robotic & Automation, pp. 1800-1805, May 1999.
9) Ed Colgate, N. Hogan, "The Interaction of Robots with Passive Environments: Application to Force Feedback Control", Proceedings of the 4th International Conference on Advanced Robotics Columbus, Ohio, Vol. B-5, pp. 465-474, June 13-15, 1989.