Development Of Hybrid Robot For Construction Works With Pneumatic Actuator

Hyeun-Seok Choi*, Chang-Soo Han*, Kye-young Lee, Sang-heon Lee****

* *Hanyang University, Department of Mechanical Engineering, Sa-1Dong, Ansan, Gyonggi-do, Korea, 425-791*
brownchoi@hanmail.net

** *Samsung Corp., Construction Equipment R&D Part, Good Friend Bank Bldg. 270-2, Seohyun-Dong, Bundang-Gu, Sungnam-Si, Gyonggi-Do, Korea, 463-771*

ABSTRACT: This paper presents a construction robot that is a hybrid type robot using pneumatic actuator. The hybrid type robot can be used in a window glass mounting, panel fixing, engine installing by gripper changing and so on. We proposed a mechanism of hybrid type robot for construction works, derived a kinematic modeling and simulated to be convinced of a propriety of its mechanism. The hybrid type robot mechanism has a wide range of workspace and precision and consists of a serial and parallel part. The developed hybrid robot has a large workspace and high strength-to-moving-weight ratio at the same time. The pneumatic actuator has been used in industry site. This is largely due to their inherent ability to provide low-cost, compact, and safe actuation. These abilities are good properties for developing robot for a construction site, such as low cost, the high rate of power/weight, usability, and simple structure. The restricting factors preventing a wider use arise from highly nonlinear dynamic properties such as air compressibility and friction effects, which combine to severely degrade responsibility and positional accuracy. The sliding mode controller is adequate to such as cylinder that is strong nonlinear property.

KEYWORDS: Construction robot, Hybrid robot, Parallel mechanism , Pneumatic Actuator, Sliding control.

1. INTRODUCTION

Recently, the robot is widely used in various fields, and is used not only in formal factory line but also in outdoor place. A construction robot is developed to help human worker in construction site. In a field of construction work, the content of work and working material are frequently changeable. And Construction worker and robot work in same place. So construction robot needs several special properties of high payload, safety, reliability, and a wide workspace. [L.H.Y] The characteristics of a hybrid type robot satisfy these needs, because the hybrid type robot has a wide workspace and high payload capable and high-precision. The hybrid type robot in this study consists of a serial and parallel part. The serial part has a wide workspace and low payload. The parallel part has high precision, a narrow workspace, and high payload capability. [Ming Z. Huang] Lee and Shah presented the kinematical structure of the 3RPS parallel manipulator and analyzed this mechanical structure.[Lee and Shah] Huang, Ling and Yang studied the characteristics of parallel-serial hybrid manipulators [Ming Z. Huang].

A pneumatic actuator has the advantages of durability, high payload-to-weight and payload-to-volume ratios, high speed and force capabilities, and a variety of power transmission methods based on a simple operational mechanism. [S. R. Pandian][H. Janocha] The environment in a field of construction work is dirty, dangerous, variety. As a result, the pneumatic actuator apply to a construction robot. However, the restricting factors preventing a wider use arise from highly nonlinear dynamic properties such as air compressibility and friction effects which combine to positional accuracy. [R. Richardson] These nonlinear dynamic properties make difficult to control pneumatic actuator. Many control algorithms are suggested for many years to control the pneumatic actuator. Junbo song and Yoshihisa ishida performed a robust sliding mode control on friction factor.[J.Song and Y. Ishida] Robert, Brown and Plummer demonstrate self-tuning control algorithm for a low-friction pneumatic actuator under the influence of gravity [R. Richardson].

In this study, we develop the construction robot for supporting the human worker at the field of a attaching heavy ceramic tile on wall. The designed robot lift and support heavy ceramic tile while human worker attach a tile on a wall. The worker can easily control the robot end-effecter position with MMI (Man Machine Interface).

The mechanism design and system schematic are present in Sec.2. The sliding controller is mentioned in Sec. 3. In Sec 4, we show the experiment result.

2. MECHANISM DESIGN & ANALYSIS

2.1 Mechanical Structure

To use a construction robot in the environment of a wide workspace and high weight, the 6 DOF robot consisting of a PRRR serial structure and 3RPS parallel structure was developed in this study. The developed robot is shown as Figure 1.

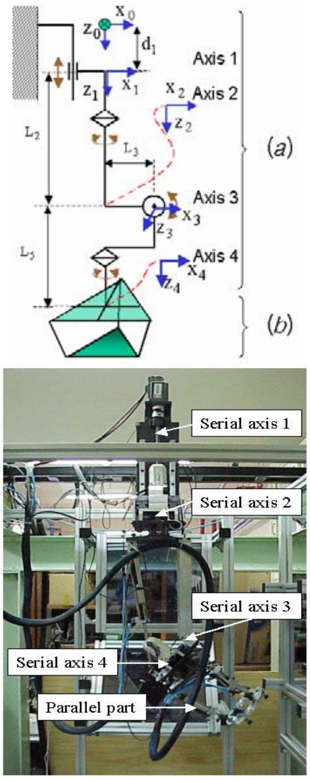


Figure 1. Serial-parallel hybrid type robot model

Using the pneumatic actuators at the serial axis 3 and the parallel part, the robot is developed to absorb the effect of the impact and the disturbance of external forces.

A parallel part is the 3RPS structure suggested by Lee and Shah [Lee and Shah]. The structure of the parallel part has three revolute joints at a fixed base and three ball joints at a moving platform, so it has 2 revolute motions and 1 prismatic motion. Figure 2 shows the parallel part of the developed robot.

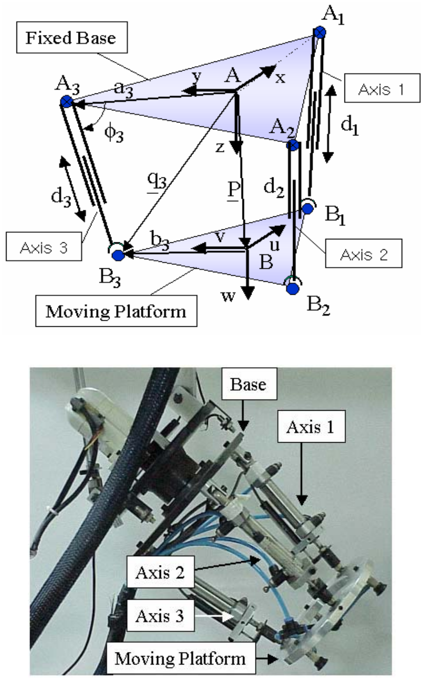
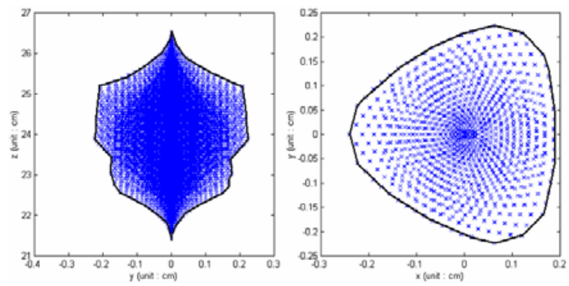


Figure 2. Parallel part of the developed robot

2.2 Kinematic Analysis

2.2.1 Forward Kinematics

The serial part has 4DOF in Figure 1 and the parallel part in Figure. 2 has 3DOF. In this system, a parallel workspace is narrow and small as shown in Figure. 3 because of the interference of each link in the parallel robot.



(a)Workspace[Y-Z Plane](b)Workspace[X-Y plane]

Figure 3. Workspace of the parallel part

As the workspace is very narrow at the Y-Z plane, the parallel part with the constraint of Z axis can be considered as 2 DOF (i.e. 2 rotational motions). Therefore, this hybrid type robot is regarded as a 6 DOF serial robot. Table 1 shows the Denavit-Hartenberg parameters.

The positioning motion part with the serial axes 1, 2 and 3 determines the desired position. The orienting motion part with the serial axis 4 and the parallel part determines the desired orientation. (Figure 4)

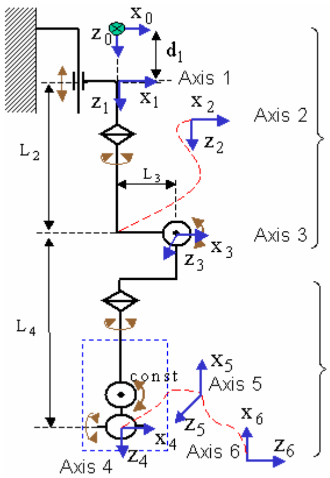


Figure 4. Kinematic analysis of the developed robot

Table 1. Denavit-Hartenberg Parameters

	i	α_{i-1}	a_{i-1}	d_i	θ_i
Positioning motion	1	0	0	d_1	0
	2	0	0	L_2	θ_2
	3	–90°	L_3	0	θ_3
Orienting motion	4	90°	$-L_3$	L_4	θ_4
	5	– 90°	0	0	θ_5
	6	– 90°	0	0	θ_6

2.2.2 Inverse Kinematics

When a point in base coordinates $\left(p_X, p_y, p_z\right)$ is given, we obtain the following Eq. (1) using Table 1

$$ {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_EP = \begin{bmatrix} p_X \\ p_Y \\ p_Z \\ 1 \end{bmatrix}, \quad {}^3_EP = \begin{bmatrix} -L_3 \\ -L_5 \\ 0 \\ 1 \end{bmatrix} \tag{1} $$

From Eq. (1), d_1, θ_2 and θ_3 are as follows:

$$ \theta_2 = A\tan 2(p_Y, p_X) \tag{2} $$

$$ a = p_X c_2 + p_y s_2 - L_3 \tag{3} $$

$$ \theta_3 = A\tan 2(-L_4, L_3) + A\tan 2(\sqrt{L_4^{\ 2} + L_3^{\ 2} + a^2}, -a) $$

(4)

$$ d_1 = p_z - L_2 - L_4 c_3 - L_3 s_3 \tag{5} $$

When a rotation matrix ${}^0_eR$ is given, ${}^3_eR$ obtained from ${}^0_3R$ using Eq.s (2), (4) and (5) is as follows:

$$ {}^3_eR = \left({}^o_3R\right)^T\,{}^0_eR \tag{6} $$

From Table 1, ${}^3_eR$ is as follows:

$$ {}^3_eR = {}^3_4R\,{}^4_5R\,{}^5_6R\,{}^6_eR \tag{7} $$

Using Eq. (6) and Eq. (7), θ_4, θ_5 and θ_6 are as follows:

$$ \theta_5 = {}^3_eR(2,1) \tag{8} $$

$$ \theta_6 = a\sin\left(-\frac{{}^3_eR(2,2)}{c_5}\right) \tag{9} $$

$$ \theta_4 = a\tan 2\left({}^3_eR(3,1),\, {}^3_eR(1,1)\right) \tag{10} $$

Using a rotation matrix of parallel manipulator from θ_5 and θ_6 , parallel link lengths are determined.

2.2.3 Dynamic Analysis

To obtain robot dynamic equation, the robot mechanical system is considered and shown in Figure. 6 (a). If the parallel part is simplified to a lumped mass, the kinetic energy of the robot can be described by the following Eq. (11).

$$ k_i = \frac{1}{2} m_i v_i^{\ T} v_i + w_i^{\ T}\,{}^cI_i w_i \quad k = \sum_{i=1}^{3} k_i \tag{11} $$

The potential energy is as follows.

$$ u_i = -m_i\,{}^0g^T\,{}^0P_{ci} + u_{ref}\ ,\ u = \sum_{i=1}^{3} u_i \tag{12} $$

From Eq.s (11) and (12), the dynamic formulation becomes:

$$ \tau_3 = \frac{d}{dt}\frac{\partial k}{\partial \dot{\theta}_3} - \frac{\partial k}{\partial \theta_3} + \frac{\partial u}{\partial \theta_3} \tag{13} $$

Therefore, the torque of the serial axis 3, τ_3, is as follows:

$$\tau_3 = \tau_a\left(\ddot{d}_1, \theta_3\right) + \tau_b\left(\dot{\theta}_2^{\,2}, \theta_3\right) + \tau_r\left(\ddot{\theta}_3\right) + \tau_g\left(g, \theta_3\right) \qquad (14)$$

where,

τ_a : torque by the acceleration, $\ddot{d}_1$

τ_b : torque by the angular velocity, $\dot{\theta}_2$

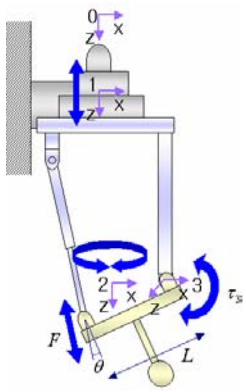
τ_c : torque by the angular acceleration, $\ddot{\theta}_3$

τ_g : torque by the gravity acceleration, g

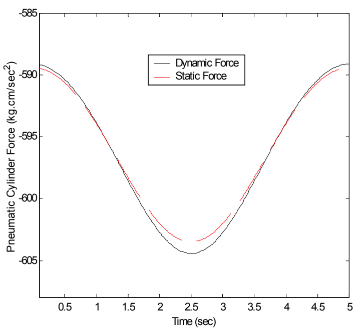
The external force by τ_3 is as follows:

$$F = \frac{\tau_3}{a \ \cos\theta} \qquad (15)$$

When the end-effector draws a circular path 5cm in diameter for 5 seconds, F is shown in Figure. 5(b).



(a) Schematic of the discrete model



(b) Simulation result of external force

Figure 5. Dynamic analysis of the developed robot

3. Pneumatic Cylinder Analysis

3.1 Dynamic Modeling of Pneumatic Cylinder

Figure. 6 shows the dynamic modeling in this study. The dynamics of the pneumatic cylinder can be described by the following second-order linear differential equation.

$$M\frac{d^2y}{dt^2} + F(y) + f(M, \dot{y}, y) + d(t) = U(t) \qquad (16)$$

where,

$d(t)$: disturbance $\quad$ $U(t)$: control input

$F(y)$: external force obtained from eq.(15)

M : mass $\quad$ $f(M, \dot{y}, y)$: friction force

y : length of piston

This dynamic equation has several nonlinear properties consisting of unknown model parameters, friction force and disturbances. As the linear control method has difficulties, the nonlinear control scheme should be needed.

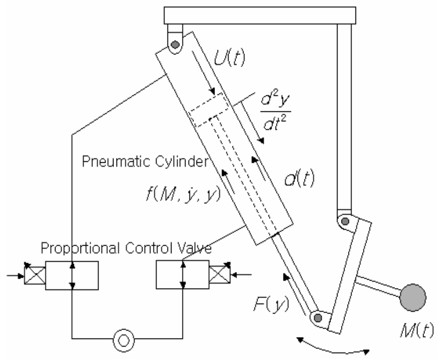


Figure 6. Schematic of pneumatic system (serial axis 3)

3.2 Sliding Mode Controller

For nonlinear controller, the following uncertain bounds for the pneumatic servo system are assumed as Eq. (17),

$$q_1 < Q < q_2 \quad Q = M^{-1} \qquad (17a)$$

$$|f(M, \dot{y}, y)| \le f_f\,|\dot{y}| + f_p\,|y| + f_s \qquad (17b)$$

$$|d(t)| \le \rho = \text{const} \qquad (17c)$$

where,

f_f : damping coefficient $\quad$ f_p : stiffness

f_s : stiction coeffiecient $\quad$ q_1, q_2, ρ : positive constants

The Lyapunov function is as follows:

$$V = \frac{1}{2}s^2 \qquad (18)$$

$$\dot{V} = s\dot{s} = s\left(c\dot{e}\right) < 0 \qquad (19)$$

$U(t)$, sliding mode control input, should be satisfied Eq. (19). Therefore, $U(t)$ is as follows:

$$U(t) = -\frac{1}{q_1 |s|} w(t) + F(y) \qquad (20)$$

where,

$$w(t) = |a_{m1} y_m| + |a_{m2} \dot{y}_m| + |b_m r| + q_1 |\rho| + c_1 |\dot{\varepsilon}| + q_2 \left(f_f |\dot{y}| + f_p |y| + f_s \right)$$

a_{m1}, a_{m2}, b_m : reference model parameter

r : reference input

y_m : reference model state variable

$\varepsilon = y - y_m$, $\dot{\varepsilon} = \dot{y} - \dot{y}_m$

$s = c_1 \varepsilon + \dot{\varepsilon}$: sliding surface

c_1 : positive constant

The objective of the sliding mode controller is that the tracking error between the plant and reference model can be guaranteed within any neighborhood of the boundary layer as time→∞. The external force and the bounded uncertainties of unknown model parameters, disturbance and friction force were applied to the control.

4. EXPERIMENTAL RESULTS

4.1 The Results of Cylinder Response

Experiments of pneumatic cylinder at the serial axis 3 were performed on a 5kg payload and a free load. In addition, the control considering the external force, *F*, was compared to the control without considering *F*.

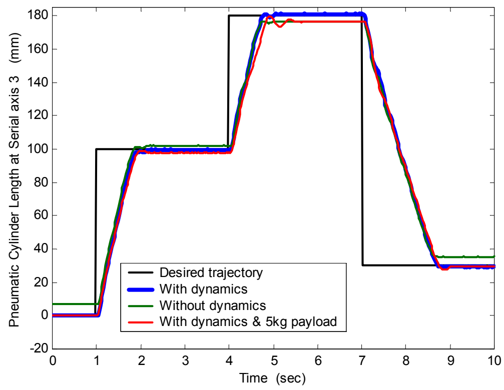


Figure 7. Step position response of the serial axis 3

Figure. 7 shows the step position response of the cylinder in serial part axis 3. The piston starts from the origin to the position of 100mm, 180mm and 40mm for 10 seconds. The control with the external force F has smaller magnitude of position error than the control without F.

4.2 The Circular Path Tracking Experiment of End-Effector (13)

To test the robot for lifting and moving heavy tile, the robot end-effector position was suspended at commanded point(z-axis :30cm, x,y:0) with the tile, and we made motion that is circle path in diameter 5cm. The tile weight was 5Kg, and it was attached on the end-effector with a vacuum pad.

Figure. 8 shows the tracking response of the pneumatic actuator at the serial axis 3. Figure. 9 shows the circular trajectory of the end-effector. The error of the end-effector was generated mostly from the pneumatic actuators, especially the serial axis 3. Therefore, the number of the pneumatic actuators to absorb the effect of the impact should be limited.

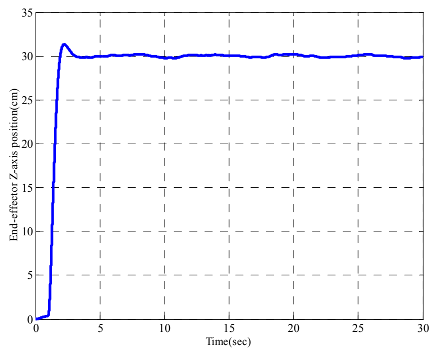


Figure 8. Suspending of end-effector position

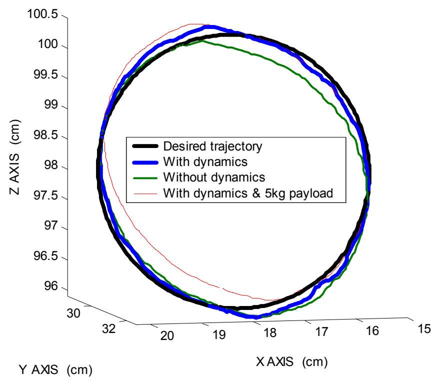


Figure 9. End-effector path control

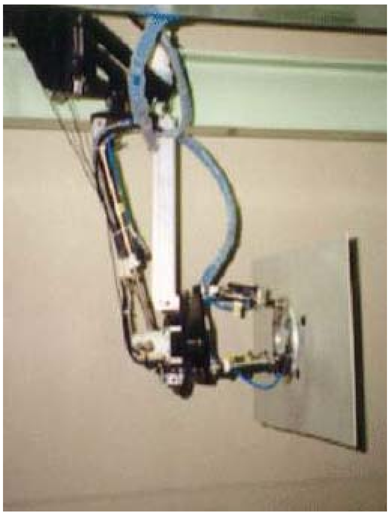


Figure 10. Suspending End-effector position

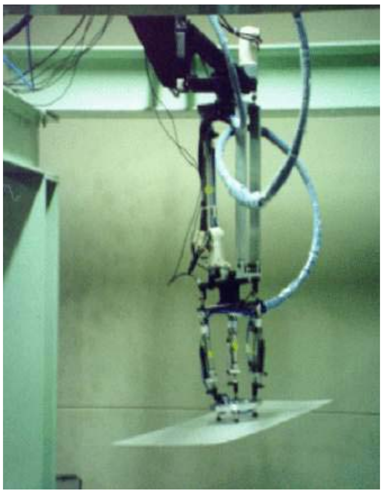


Figure 11. End-effector path control

5. CONCLUSION

In this paper, the hybrid type construction robot using pneumatic actuator and servo motor was developed to support the human worker for a work of tile or panel material in construction field.

The hybrid type robot has a large workspace and a resistance to a payload. The pneumatic actuators were controlled by the sliding mode controller. The robot dynamics and the nonlinear properties of pneumatic actuator were applied for the sliding mode controller.

In experiment, the proposed construction robot lifts the tile (5kg) and moves it through the circle path. The designed sliding controller is adequate for a pneumatic cylinder control.(Figure 10, 11)

A position resolution of the designed robot system is less than 3mm. It is not high precision level, but this robot system can be used for a supporting human worker in some construction works that are not needed high precision.

6. ACKNOWLEDGEMENTS

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