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Control Design for Industrial Parallel Manipulators

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ABSTRACT:Parallel robots have received increasing attention due to their inherent advantages over conventional serial mechanisms, such as high rigidity, high load capacity, high velocity, and high precision. A definite advantage of parallel robots is that, in most cases, actuators can be placed on the truss, thus achieving a limited weight for the moving parts, making it possible for parallel robots to move at high speed. The simulation showed promising results when using enough accurate mechanical models.

KEYWORDS: Parallel manipulator, DAE, PID.

I. INTRODUCTION

Up to now, robotics are still receiving the attention of many researchers manufacturers because of their great advantages in many fields [1-25]. Parallel manipulators are multibody systems with a loop structure. Their motions are described by differential-algebraic equations [26-35]. The tracking control of chain robots has been studied extensively [36-45]. However, controlling parallel manipulators to follow the desired trajectory has been rarely studied. In this paper, the authors introduce using the PID controller to control parallel manipulators

II. MATHEMATICAL MODEL

The motion equation of the dynamic models is rewritten in the following:

$$\mathbf{M}(\mathbf{s})\ddot{\mathbf{s}} + \mathbf{C}(\mathbf{s},\dot{\mathbf{s}})\dot{\mathbf{s}} + \mathbf{g}(\mathbf{s}) + \mathbf{\Phi}_s^T(\mathbf{s})\boldsymbol{\lambda} = \boldsymbol{\tau} \quad (1)$$

$$\mathbf{f}(\mathbf{s}) = \mathbf{0} \quad (2)$$

Where $\mathbf{M}(\mathbf{s}),\mathbf{C}(\mathbf{s},\dot{\mathbf{s}})$ are square matrices of size $n\times n$, $\mathbf{\Phi}_s(\mathbf{s})$ is a rectangular matrix of size $r\times n$. $\boldsymbol{\tau}$, $\mathbf{s}$ are column vectors with n elements, $\mathbf{f}$ are column vectors with r elements. The residual constraint coordinates $\mathbf{s}$ and the actuation torque are written as.

Denoting $F_a(\mathbf{s}) = \dfrac{\partial \mathbf{f}}{\partial \mathbf{q}_a}$; $F_z(\mathbf{s}) = \dfrac{\partial \mathbf{f}}{\partial \mathbf{z}}$, the Jacobi matrix $F_s(\mathbf{s})$ is rewritten as below:

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we define :

$$\mathbf{R}(\mathbf{s}) = \begin{bmatrix} \mathbf{E} \\ F_z^{-1}(\mathbf{s})F_a(\mathbf{s}) \end{bmatrix} \quad (3)$$

where **E** is a unit matrix of size $f\times f$.

We have:

$$\mathbf{R}^T(\mathbf{s})F_s^T(\mathbf{s}) = \mathbf{0} \quad (4)$$

$$\dot{\mathbf{s}} = \mathbf{R}(\mathbf{s})\dot{\mathbf{q}}_a \quad (5)$$

Multiply the two sides of equation (1) by the matrix $\mathbf{R}^T(\mathbf{s})$ while simultaneously substituting equation (5)and its time derivative into equation (1), we get :

$$\bar{\mathbf{M}}(\mathbf{s})\ddot{\mathbf{q}}_a + \bar{\mathbf{C}}(\mathbf{s},\dot{\mathbf{s}})\dot{\mathbf{q}}_a + \bar{\mathbf{g}}(\mathbf{s}) = \boldsymbol{\tau}_a \quad (6)$$

where:

$$\bar{\mathbf{M}}(\mathbf{s}) := \mathbf{R}^T(\mathbf{s})\mathbf{M}(\mathbf{s})\mathbf{R}(\mathbf{s})$$
$$\bar{\mathbf{C}}(\mathbf{s},\dot{\mathbf{s}}) := \mathbf{R}^T(\mathbf{s})\left[\mathbf{M}(\mathbf{s})\dot{\mathbf{R}}(\mathbf{s},\dot{\mathbf{s}}) + \mathbf{C}(\mathbf{s},\dot{\mathbf{s}})\mathbf{R}(\mathbf{s})\right] \quad (7)$$
$$\bar{\mathbf{g}}(\mathbf{s}) := \mathbf{R}^T(\mathbf{s})\mathbf{g}(\mathbf{s})$$

Matrices $\bar{\mathbf{M}}(\mathbf{s}),\bar{\mathbf{C}}(\mathbf{s},\dot{\mathbf{s}})$ have the following properties: matrix $\bar{\mathbf{M}}(\mathbf{s})$ is a positive definite symmetric matrix, matrix $\dot{\bar{\mathbf{M}}}(\mathbf{s}) - 2\bar{\mathbf{C}}(\mathbf{s},\dot{\mathbf{s}})$ is a skewed symmetric matrix. We will use equation (6) and the above properties to design controllers for the parallel robot.

III. CONTROL DESIGN

We choose the control rule u (t) as below

$$\mathbf{u}(t) = \bar{\mathbf{M}}(\mathbf{s})\mathbf{v} + \bar{\mathbf{C}}(\mathbf{s},\dot{\mathbf{s}})\dot{\mathbf{q}}_a + \bar{\mathbf{g}}(\mathbf{s}) \quad (8)$$

With

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$$\mathbf{v} = \ddot{\mathbf{q}}_a^d - \mathbf{K}_D\dot{\mathbf{e}} - \mathbf{K}_P\mathbf{e} - \mathbf{K}_I\int_0^t \mathbf{e}d\tau \quad (9)$$

where $\mathbf{K}_D$, $\mathbf{K}_P$, $\mathbf{K}_I$ are positive definite diagonal matrices:

$$\mathbf{K}_P = diag\left(k_{P1}, k_{P2}, \ldots, k_{Pna}\right), \mathbf{K}_D = diag\left(k_{D1}, k_{D2}, \ldots, k_{Dna}\right), \mathbf{K}_I =$$

$\bar{\mathbf{M}}$ is a positive matrix, we obtain:

$$\ddot{\mathbf{e}} + \mathbf{K}_D\dot{\mathbf{e}} + \mathbf{K}_P\mathbf{e} + \mathbf{K}_I\int_0^t \mathbf{e}d\tau = \mathbf{0} \quad (10)$$

Taking derivative both sides of ((10) w.r.t. time yields:

$$\dddot{\mathbf{e}} + \mathbf{K}_D\ddot{\mathbf{e}} + \mathbf{K}_P\dot{\mathbf{e}} + \mathbf{K}_I\mathbf{e} = \mathbf{0} \quad (11)$$

Since $\mathbf{K}_D, \mathbf{K}_P, \mathbf{K}_I$ are diagonal matrices,we deduce third-order differential equations as below:

$$\dddot{e}_{ai} + k_{Di}\ddot{e}_{ai} + k_{Pi}\dot{e}_{ai} + k_{Ii}e_{ai} = 0 \quad (i=1,2,\ldots,n_a) \quad (12)$$

Equations (12) are the linear differential equations of the constant coefficient. Characteristic equations take the following form:

$$\lambda_i^3 + k_{Di}\lambda_i^2 + k_{Pi}\lambda_i + k_{Ii} = 0. \quad (i=1,2,\ldots, n_a) \quad (13)$$

According to the Hurwitz stability criteria, the conditions for characteristic equation solutions to have a negative part are:

$$k_{Di} > 0,\ k_{Pi} > 0,\ k_{Ii} > 0,\ k_{Di}k_{Pi} - k_{Ii} > 0 \quad (14)$$

$(i = 1,2,\ldots, n_a)$

Thus, if the coefficients are chosen such that the conditions (14) are satisfied, the differential equations (12) will be exponentially stable.

PID controller:

$$\mathbf{K}_P = 3500\,\mathrm{diag}(1,1,1); \mathbf{K}_I = 350\,\mathrm{diag}(1,1,1); \mathbf{K}_D = 250\,\mathrm{diag}(1,1,1);$$

The trajectory of the moving table is given as below:

$$x_P = -0.05\cos(2\pi t);\ y_P = 0.05\sin(2\pi t); z_P = -0.5(m)$$

The control diagram for the manipulator is shown in Fig. 1.

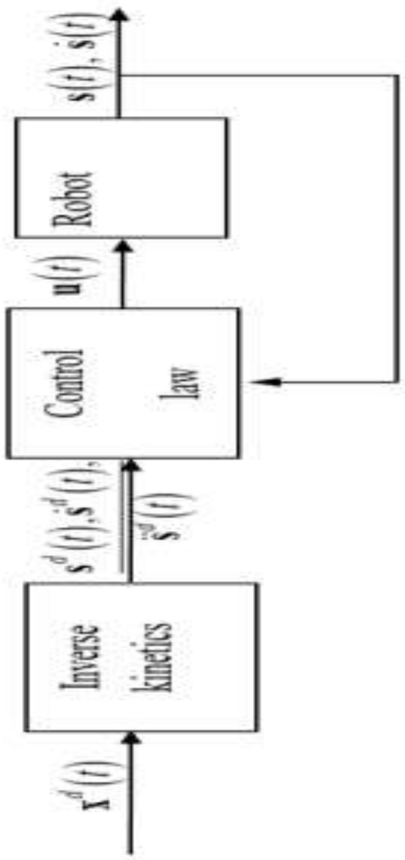

Fig. 1. Control diagram

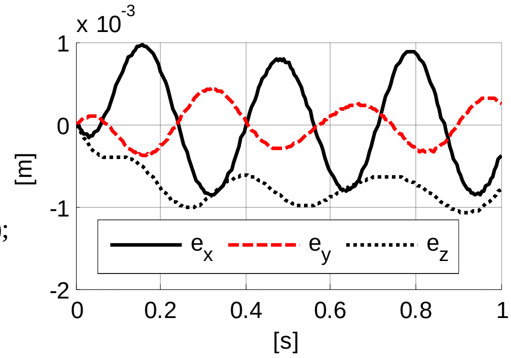

Fig. 2. Position error

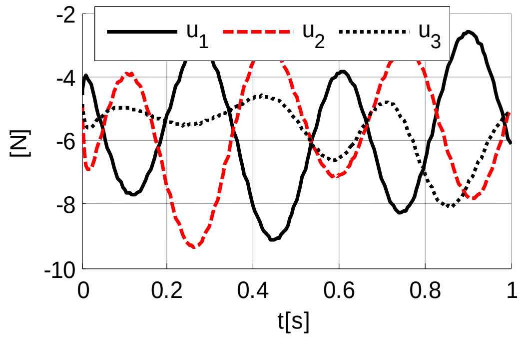

Fig. 3. Torque control

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IV. CONCLUSION

This paper presents the construction of controllers for parallel robot manipulators based on a system of Differential-Algebraic Equations. The new matrix form of Lagrangian equations with multipliers for constrained multibody systems was used to derive dynamic equations of the parallel robot manipulator using computer software packages. The controller for spatial robot manipulators based on inverse dynamics was developed. The control law to compensate for uncertainties in the parallel robot manipulators is then presented in detail. The 3-PRS spatial parallel robot manipulator controller was investigated through the numerical simulation with MATLAB /Simulink.The simulation results showed a reasonable control quality when using accurate mechanical models.

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REFERENCES

[1]. Siciliano, B., Sciavicco, L., Villani, L., & Oriolo, G. (2009). Trajectory Planning. Robotics: Modelling, Planning and Control, 161-189.
[2]. Siciliano, B., Sciavicco, L., Villani, L., & Oriolo, G. (2009). Differential kinematics and statics. Robotics: Modelling, Planning and Control, 105-160.
[3]. Bruno, S., Lorenzo, S., Luigi, V., & Giuseppe, O. (1994). Robotics: modelling, planning and control, 2010. Cited on, 1.
[4]. Alcocer, A., Robertsson, A., Valera, A., & Johansson, R. (2003). Force estimation and control in robot manipulators. IFAC Proceedings Volumes, 36(17), 55-60.
[5]. Perrusquía, A., Yu, W., & Soria, A. (2019). Position/force control of robot manipulators using reinforcement learning. Industrial Robot: the international journal of robotics research and application.
[6]. Anderson, R. J., & Spong, M. W. (1988). Hybrid impedance control of robotic manipulators. IEEE Journal on Robotics and Automation, 4(5), 549-556.
[7]. Kiguchi, K., & Fukuda, T. (2000). Position/force control of robot manipulators for geometrically unknown objects using fuzzy neural networks. IEEE Transactions on Industrial Electronics, 47(3), 641-649.
[8]. Yang, M., Yang, E., Zante, R. C., Post, M., & Liu, X. (2019, September). Collaborative mobile industrial manipulator: a review of system architecture and applications. In 2019 25th International Conference on Automation and Computing (ICAC) (pp. 1-6). IEEE.
[9]. Miro, J. V., & White, A. S. (2002). Modelling an industrial manipulator a case study. Simulation practice and theory, 9(6-8), 293-319.
[10]. Lasky, T. A., & Hsia, T. C. (1994, June). Application of a digital signal processor in compliant cartesian control of an industrial manipulator. In Proceedings of 1994 American Control Conference-ACC'94 (Vol. 3, pp. 2439-2443). IEEE.
[11]. Álvarez-Martínez, D. (2018, June). Modelling the kinematic properties of an industrial manipulator in packing applications. In 2018 IEEE 14th International Conference on Control and Automation (ICCA) (pp. 1028-1033). IEEE.
[12]. Lu, Z. (2021). Iterative learning control algorithm for optimal path industrial manipulator. Journal of Intelligent & Fuzzy Systems, 40(4), 5875-5882.
[13]. Srinivas, G. L., & Javed, A. (2020). Topology optimization of rigid-links for industrial manipulator considering dynamic loading conditions. Mechanism and Machine Theory, 153, 103979.
[14]. Matko, D., Kamnik, R., & Bajd, T. (1999, July). Adaptive impedance force control of an industrial manipulator. In ISIE'99. Proceedings of the IEEE International Symposium on Industrial Electronics (Cat. No. 99TH8465) (Vol. 1, pp. 129-133). IEEE.
[15]. Srinivas, G. L., & Javed, A. (2019). Topology optimization of industrial manipulator-link considering dynamic loading. Materials Today: Proceedings, 18, 3717-3725.
[16]. Srinivas, G. L., & Javed, A. (2019). Topology optimization of industrial manipulator-link considering dynamic loading. Materials Today: Proceedings, 18, 3717-3725.
[17]. Cheng, H. H. (1994). Real-time manipulation of a hybrid serial-and-parallel-driven redundant industrial manipulator.
[18]. Beniak, R., Wach, P., & Wosik, P. (2001, October). Robust, direct torque control of induction motor drives in application to industrial manipulator. In Proceedings of the Second International Workshop on Robot Motion and Control. RoMoCo'01 (IEEE Cat. No. 01EX535) (pp. 207-212). IEEE.

[19]. Wang, L., & Kang, Y. Y. (2013). Modeling and simulating industrial manipulator based on ADAMS. In Applied Mechanics and Materials (Vol. 339, pp. 153-156). Trans Tech Publications Ltd.

[20]. Liu, Y., Xu, H., Geng, C., & Chen, G. (2017, December). A modular manipulator for industrial applications: Design and implement. In 2017 2nd International Conference on Robotics and Automation Engineering (ICRAE) (pp. 331-335). IEEE.

[21]. Eliot, E., BBVL, D., & Parhi, D. R. (2012). Design & kinematic analysis of an articulated robotic manipulator.

[22]. Brethé, J. F., & Dakyo, B. (2002, September). A stochastic ellipsoid approach to repeatability modelisation of industrial manipulator robots. In IEEE/RSJ International Conference on Intelligent Robots and Systems (Vol. 2, pp. 1608-1613). IEEE.

[23]. Krishnasamy, J., Hosek, M., & Moura, J. (2011, April). Application of optimal trajectory algorithms to a solar-panel handling industrial manipulator: a case study. In 2011 IEEE Conference on Technologies for Practical Robot Applications (pp. 40-44). IEEE.

[24]. Azman, N. H., Oktaviandri, M., & Ramedan, M. R. (2022). SCADA System for Industrial Manipulator PLC Trainer. In Enabling Industry 4.0 through Advances in Mechatronics (pp. 375-385). Springer, Singapore.

[25]. Guo, M., Zhang, H., Feng, C., Liu, M., & Huo, J. (2018). Manipulator residual estimation and its application in collision detection. Industrial Robot: An International Journal.

[26]. De Jalon, J. G., & Bayo, E. (2012). Kinematic and dynamic simulation of multibody systems: the real-time challenge. Springer Science & Business Media.

[27]. Merlet, J. P., Gosselin, C., & Huang, T. (2016). Parallel mechanisms. In Springer handbook of robotics (pp. 443-462). Springer, Cham.

[28]. Ceccarelli, M. (2004). Fundamentals of the mechanics of robots. In Fundamentals of Mechanics of Robotic Manipulation (pp. 73-240). Springer, Dordrecht.

[29]. Huston, R. L. (1991). Multibody dynamics—modeling and analysis methods.

[30]. Schiehlen, W. (2007). Research trends in multibody system dynamics. Multibody System Dynamics, 18(1), 3-13.

[31]. Kamman, J. W., & Huston, R. L. (2001). Multibody dynamics modeling of variable length cable systems. Multibody System Dynamics, 5(3), 211-221.

[32]. Marques, F., Flores, P., Claro, J. C., & Lankarani, H. M. (2019). Modeling and analysis of friction including rolling effects in multibody dynamics: a review. Multibody System Dynamics, 45(2), 223-244.

[33]. Skrinjar, L., Slavič, J., & Boltežar, M. (2018). A review of continuous contact-force models in multibody dynamics. International Journal of Mechanical Sciences, 145, 171-187.

[34]. Schutte, A., & Udwadia, F. (2011). New approach to the modeling of complex multibody dynamical systems.

[35]. Liu, J. W., Liu, J. P., Shu, X. B., Mikkola, A., & Ren, G. X. (2019). An efficient multibody dynamic model of three-dimensional meshing contacts in helical gear-shaft system and its solution. Mechanism and Machine Theory, 142, 103607.

[36]. Kelly, R., Davila, V. S., & Perez, J. A. L. (2005). Control of robot manipulators in joint space. Springer Science & Business Media.

[37]. Chen, Y., Luo, X., Han, B., Luo, Q., & Qiao, L. (2020). Model Predictive Control With Integral Compensation for Motion Control of Robot Manipulator in Joint and Task Spaces. IEEE Access, 8, 107063-107075.

[38]. Zhao, Y., & Bai, Z. F. (2011). Dynamics analysis of space robot manipulator with joint clearance. Acta Astronautica, 68(7-8), 1147-1155.

[39]. Khatib, O., & Burdick, J. (1986, April). Motion and force control of robot manipulators. In Proceedings. 1986 IEEE international conference on robotics and automation (Vol. 3, pp. 1381-1386). IEEE.

[40]. Rahimi, H. N., Howard, I., & Cui, L. (2018). Neural adaptive tracking control for an uncertain robot manipulator with time-varying joint space constraints. Mechanical Systems and Signal Processing, 112, 44-60.

[41]. Sadeghian, H., Villani, L., Keshmiri, M., & Siciliano, B. (2013). Task-space control of robot manipulators with null-space compliance. IEEE Transactions on Robotics, 30(2), 493-506.

[42]. Shen, Y., & Huper, K. (2005, July). A joint space formulation for compliant motion control of robot manipulators. In IEEE International Conference Mechatronics and Automation, 2005 (Vol. 1, pp. 362-369). IEEE.

[43]. Wang, L., Chai, T., & Yang, C. (2011). Neural-network-based contouring control for robotic manipulators in operational space. IEEE Transactions on Control Systems Technology, 20(4), 1073-1080.

[44]. Chiaverini, S., & Sciavicco, L. (1993). The parallel approach to force/position control of robotic manipulators. IEEE Transactions on Robotics and Automation, 9(4), 361-373.

[45]. Corradini, M. L., Fossi, V., Giantomassi, A., Ippoliti, G., Longhi, S., & Orlando, G. (2012). Discrete time sliding mode control of robotic manipulators: Development and experimental validation. Control Engineering Practice, 20(8), 816-822