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Intelligent Cascade Control of Hydraulically Driven Parallel Robot Platform

Novak Nedic+, Vladimir Stojanovic+, Dragan Prsic+ and Ljubisa Dubonjic+

+Department of Energetics and Automatic Control, University of Kragujevac, Faculty of mechanical and civil engineering in Kraljevo, Dositejeva 19, 36000 Kraljevo, Serbia, E-Mail: vladostojanovic@open.telekom.rs

Abstract* – This paper presents an optimal tuning of cascade load force controllers for hydraulically driven parallel robot platform. A PID control technique is usually applied in practice for control of a 6-DOF parallel robot platform. The proposed parameter search scheme is based on a Cuckoo Search (CS) algorithm, which has received a lot of attention recently in the evolutionary computation area due to its superiority in solving various non-convex problems. Simulation results show the advantages of proposed optimal tuned cascade controllers to solve the formulated tracking problem in relation to the classical PID controllers.

***Key words:* parallel robot platform, controller tuning, hydraulically control systems, cuckoo search algorithm**

I. INTRODUCTION

The hydraulically driven parallel robot platform is obtained through a generalization of the mechanism proposed by Stewart as a flight simulator [1]. As shown in Fig. 1. this spatial platform mechanism consists of a fixed base platform and an upper moving platform. The six extendable legs connect these platforms. Besides greater stiffness and accuracy, these robot platforms have high payload-weight ratio due to parallel linkage. The payload and positioning errors would be accumulated without parallel linkage.

Fig.1. A 3D model of a 6-DOF parallel robot platform

The parallel robot control strategy may be designed from two frameworks. One is to design a controller based on the legspace coordinates and the other is based on the workspace coordinates. The control strategy based on the workspace coordinates has a limitation to the real-time application due to difficulty in obtaining information on the upper moving platform. However, the upper moving platform of a parallel platform can move with the six desired degrees of freedom (DOF) if the lengths of the all legs are well controlled. Bearing this in mind, the control strategy study of the parallel robot platform rather is based on the legspace coordinates [2].

Since dynamics of the hydraulically driven 6-DOF parallel robot platform consist of two parts, the designed controller should take into account not only the mechanical dynamics, but also the hydraulic dynamics by using the cascade control method [2].

However, the PID controllers in inner control loops of the proposed cascade controllers, are often poorly tuned owing to highly changing dynamics of parallel robot platform caused by large nonlinearities and changes of parameters during motion. Due to a change of the system parameters, the conventional PID controllers result in sub-optimal corrective actions and hence require retuning. In control design of continuous processes, the tuning of controller parameters could be done with traditional methodology. The models of such processes can be linearized in an equilibrium point. However, there are the systems that cannot be linearized around an equilibrium point, because there is no equilibrium point. If a linear approximation is found, the resulting model will be valid only for a small region around the linearization point. Nonlinearity, in conjunction with the increased complexity due to the mutual influence between the system's variables imposes difficulties to the task of optimization with the use of classical optimization techniques.

Therefore, it is necessary to use non classical tuning methods to achieve the best overall control strategy. As an alternative, metaheuristic algorithms are applied for the quality controller tuning. Authors use Cuckoo Search (CS) to tuning the controller parameters. CS represents a new metaheuristic algorithm which is nature-inspired by some species of a bird family called cuckoo because of their special lifestyle and aggressive reproduction strategy. This algorithm is developed by Yang and Deb [3] and their studies have shown better efficiency of the CS algorithm in finding a global optimum. This artificial technology can obtain the optimal parameters, especially for plants with time variance, time delay, nonlinearity and coupling. The main advantage of these algorithms over the others traditionally used in controller design is that they do not require gradients and convexity of the problem and they will find a global optimum [4].

It is demonstrated by simulation results from MATLAB model that the proposed approach is considerably simple and convenient to use.

II. A CASCADE CONTROL ALGORITHM

As mentioned in the introduction, it is necessary to design a control algorithm based on the legspace coordinates of the hydraulically driven parallel robot platform. Besides the mechanical dynamics, the designed controller should also take into account the hydraulic dynamics.

In the 6-DOF hydraulically driven parallel robot platform, six hydraulic cylinders act on the same load (the upper moving platform) so that the outputs and control of the six actuators affect one another. Therefore, the loads of the six actuators are coupled. The coupling, which is embedded in one of the actuators, makes this actuator a variable load system with a time-dependent external disturbance. Hence, the designed controller should be robust to parameter perturbation, be able to reject the external disturbance and sufficiently take into account the hydraulic dynamics. The schematic diagram of the cascade control for the single hydraulic actuator, based on the input-output linearization, is shown in Fig.2.

As depicted in Fig. 2, the cascade F_L control consists of two loops. First, the inner-loop control, which is the actual actuator control loop, has the objective of controlling the actuator pressure–difference–force F_L by using the input–output linearization, independent of the resulting motions of the load. This means that it gives the actuator the character of a force generator. Second, the outer–loop control is concerned with the stabilizing control of the actuator load and the compensation of external forces F_{ext}.

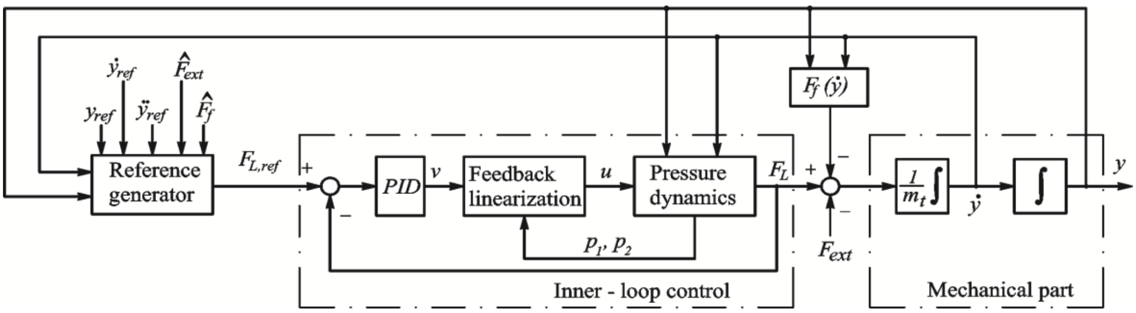

Fig. 2. Structure block diagram of the cascade control based on input output linearization

The intuitive and simple basis of the input-output linearization approach to non-linear control design is to find a direct relation between output from the subsystem "pressure dynamics" F_L and the control input u, see Fig.2. To generate such a direct relationship, the output equation:

$$F_L = A_a(p_a - \alpha p_b), \quad \alpha = A_b / A_a \qquad (1)$$

is differentiated so often as the input u does not explicitly appear. Once an explicit relationship:

$$\begin{aligned}\dot{F}_L &= -A_1^2\left[\frac{\beta}{V_1} - \alpha^2\frac{\beta}{V_2}\right]\dot{y} - \left[\frac{\beta}{V_1} + \alpha\frac{\beta}{V_2}\right]c_L(p_1 - p_2) + \\ &+ A_1\left[\frac{\beta}{V_1}c_{v1}\sqrt{|p_s - p_1|} + \alpha\frac{\beta}{V_2}c_{v2}\sqrt{|p_2 - p_R|}\right]u =: v\end{aligned} \qquad (2)$$

between u and F_L is obtained, the corresponding output derivative is set to the new input v, also termed virtual or artificial control input, and the relationship is solved with respect to u to give the control law for input-output linearisation. In (2) c_{vi} denotes the flow coefficient ($i = 1, 2$) while c_L represents the internal leakage flow coefficient. The area ratio of the asymmetric piston is $\alpha = A_2/A_1$, where A_1 is the effective area of the head side of the piston and A_2 is the effective area of the rod side of the piston. Using this linear relationship, the system output can easily be made to exhibit the desired behaviour. For this, the virtual signal v can be selected to be an appropriate function of F_L and $F_{L,ref}$. In other to achieve position tracking, the desired force should be chosen to be [5]:

$$F_{L,ref} = m_t\ddot{y}_{ref} - k_v(\dot{y} - \dot{y}_{ref}) - k_p(y - y_{ref}) + \hat{F}_f(\dot{y}) \qquad (3)$$

where $\hat{F}_f(\dot{y})$ is an estimate of friction forces in the cylinder, combined with the proportional-integral-differential feedback, with adjustable gains P, I and D:

$$v = Pe(t) + I\int_0^T e(t)dt + D\frac{de(t)}{dt} \qquad (4)$$

in which $e(t) = F_{Lref} - F_L$.

Compared to the classical control strategy, where is necessary to perform appropriate adjustments in a small range for a favorable performance, there is no modification for the proposed cascade controller, due to its high robustness. The performance of proposed cascade load force controller is dependent on its parameters P, I and D thus determination of these parameters is essential to the cascade controller design. This problem will be considered in the following sections of the paper.

III. OPTIMAL TUNING OF CASCADE CONTROLLERS

Some properties of the parallel robot platform, such as high dimensionality, high nonlinearity, parameter interaction, and the presence of stochastic disturbances make classical optimization approaches insufficient. The presence of disturbances and uncertainty, which are present in the model, cannot be modeled analytically. Heuristic/approximate methods are good candidates to obtain good solutions for our problem which is too complex to be solved in an exact manner.

The basic steps of the CS can be summarized as the pseudo code shown in next Table 1.

BEGIN CS
Objective function $f(x)$, $x = (x_1, \quad x_2, \quad \ldots, \quad x_d)$;
Generate initial population of n host nets x_i, $i = \overline{1,n}$
  WHILE (stop criterion)
  Get a Cuckoo randomly by Lévy flights;
  Evaluate its quality/fitness F_i;
  Choose a nest among n (say j) randomly;
    IF $F_i \geq F_j$
    replace j by the new solution;
    END
  Abandon a fraction (p) of worse nests
  [and build new ones at new locations via Lévy flights]
  Keep the best solutions (or nests with quality solutions);
  Rank the solutions and find the current best;
  END WHILE
Display the obtained results.
END CS

Table 1. Pseudo code of CS algorithm

CS randomly chooses controller parameters after which, the corresponding position errors are calculated. Since the positions of six hydraulic cylinders are controlled then the objective function must take into account the position errors of all cylinders:

$$f(x) = \int_0^T \|\varepsilon(t)\| dt \tag{5}$$

where $\varepsilon(t) = [\varepsilon_1(t) \quad \ldots \quad \varepsilon_6(t)]^T$ represents the position error vector in which $\varepsilon_i(t)$, $i = \overline{1,6}$ denotes the position error of $i-$th leg and T represents the time interval in which the optimization is performed.

Now the optimization-based cascade controller design considered in this paper is stated as follows: find the optimal controller parameters which minimizes the objective function (5), where

$$\begin{aligned} x^T &= [x_1 \quad x_2 \quad \ldots \quad x_{18}] = \\ &= [P_1 \quad I_1 \quad D_1 \quad P_2 \quad I_2 \quad D_2 \quad \ldots \quad P_6 \quad I_6 \quad D_6] \end{aligned} \tag{6}$$

denotes the design parameter vector. The total number of design variables are 18, since each of the six controllers has three tuning parameters. The search space is given by $X := \{x \in \mathbb{R}^{18} \mid 10^3 \leq x_i \leq 10^6, \ i = \overline{1,18}\}$ based on the control problem setting.

IV. SIMULATION RESULTS

The proposed control law is simulated using Matlab's Simulink model. To verify the effectiveness of the proposed optimal tuned cascade scheme, it is made a comparative in relation to the well-tuned PID controllers, which is widely used in practice [6,7]. The system parameters are selected based upon their actual values: areas of the head and rod side of the piston $A_1 = 5 \cdot 10^{-3} m^2$ and $A_2 = 2.3 \cdot 10^{-3} m^2$, respectively, piston stroke $L = 0.7m$, bulk modulus of the fluid $\beta_e = 700MPa$, supply pressure $p_s = 2.5MPa$, mass of the upper platform $m_p = 550kg$, mass of the piston $m_{pi} = 2kg$, mass of the cylinder $m_{Ci} = 45kg$, moment of inertia of the cylinder $I_{Cxi} = 0.2kgm^2$, $I_{Cyi} = 6kgm^2$, $I_{Czi} = 6kgm^2$ moment of inertia of the piston $I_{Pxi} = 0.03kgm^2$, $I_{Pyi} = 3.5kgm^2$, $I_{Pzi} = 3.5kgm^2$, moment of inertia of the upper platform $I_{Px} = 3kgm^2, I_{Py} = 28kgm^2, I_{Pz} = 28gm^2$, radius of the base platform $R_B = 1.3m$, radius of the upper platform $R_P = 0.8m$. The reference trajectory is chosen to be:

$$\begin{aligned} x_{ref} &= 0.1\sin(2\pi t) \text{ [m]}, \\ y_{ref} &= 0.15\sin(2\pi t + \pi/2) \text{ [m]} \\ z_{ref} &= 1 + 0.15\sin(2\pi t) \text{ [m]}, \\ \varphi_{ref} &= \theta_{ref} = -\psi_{ref} = 0.2\sin(3t) \text{ [rad]} \end{aligned} \tag{7}$$

The cascade algorithm which use the CS method, have the following values: the initial population of nests are $n = 20$, the egg laid is discovered by the host bird with a probability $p = 0.25$. The optimal tuned parameters of the cascade controllers are given in the Table 2.

	P	**I**	**D**
Controller 1	$5.561 \cdot 10^5$	$4.383 \cdot 10^3$	$2.128 \cdot 10^4$
Controller 2	$4.264 \cdot 10^5$	$3.583 \cdot 10^3$	$1.255 \cdot 10^4$
Controller 3	$4.167 \cdot 10^5$	$2.245 \cdot 10^3$	$5.027 \cdot 10^3$
Controller 4	$5.286 \cdot 10^5$	$3.047 \cdot 10^3$	$2.985 \cdot 10^4$
Controller 5	$4.521 \cdot 10^5$	$4.587 \cdot 10^3$	$2.194 \cdot 10^4$
Controller 6	$6.233 \cdot 10^5$	$4.254 \cdot 10^3$	$3.477 \cdot 10^4$

Table 2. Final values of design variables

The position errors of six legs, using optimal-tuned cascade controllers and classical tuned PID controllers are shown in Figs. 3 and 4. Detailed analysis of the position errors, have shown that with classical PID control strategy, position errors are 9.2%, but after applying proposed optimal algorithm, position errors are only 1.3%.

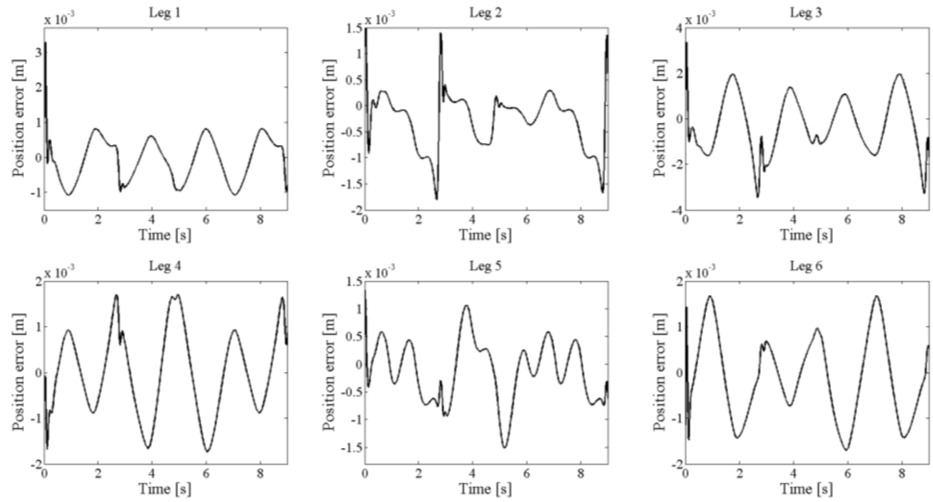

Fig. 3. Position error of the extensible actuators using optimal tuned cascade controllers

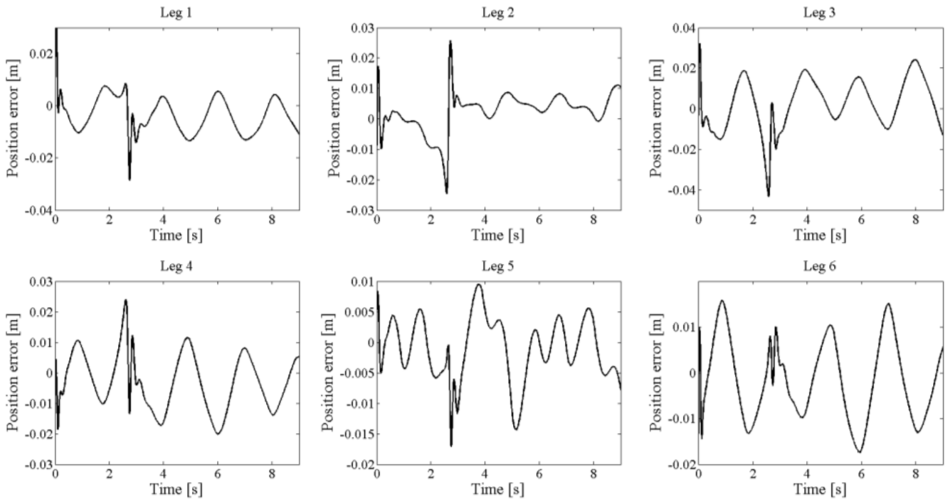

Fig. 4. Position error of the extensible actuators using classical tuned PID controllers

V. CONCLUSION

In order to realize reference trajectory of the 6-DOF parallel robot platform, we have proposed an optimal tuned cascade control strategy in the legspace. We have presented an optimal parameter search based on Cuckoo Search. Detailed simulation results have shown that such optimal tuned cascade controllers outperform the widely used classical tuned PID controllers and exhibit satisfactory tracking performance.

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REFERENCES

[1] D. Stewart, “A platform with six degrees of freedom”, *Proceedings of the Institution of Mechanical Engineers, Journal of Power and Energy*, vol.180(15), 1965, pp. 371–386
[2] H.B. Guo, Y.G. Liu, G.R. Liu, H.R. Li, “Cascade control of a hydraulically driven 6-DOF parallel robot manipulator based on a sliding mode”, *Control Engineering Practice*, vol. 16(9), 2008, pp.1055-1068
[3] Yang X.S, Deb S., “Engineering optimisation by Cuckoo Search”, *International Journal of Mathematical Modelling and Numerical Optimisation*, vol. 2(4) (2010) 330–343
[4] N. Nedic, D. Prsic, Lj. Dubonjic, V. Stojanovic, V. Djordjevic, “Optimal cascade hydraulic control for a parallel robot platform by PSO”, *The International Journal of Advanced Manufacturing Technology*, vol. 72(5-8), 2014, pp. 1085-1098
[5] Jelali, M., Kroll, A., *Hydraulic Servo-systems*, Springer, Berlin, 2002
[6] V.Filipovic, N.Nedic, *PID regulators*, Faculty of Mechanical Engineering Kraljevo, 2008
[7] N.Cominos, P.Munro, “PID Controllers: Recent Tuning Methods and Design to Specification”, *IEEE Proceedings, Control Theory and Applications*. vol. 149, 2002, pp. 46–53