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OPTIMAL ORIENTATION IN THE SPACE FOR GET ENERGETIC SAVE-UP IN THE STEWART-GOUGH PLATFORM ACTUATORS

ORIENTACIÓN ÓPTIMA EN EL ESPACIO PARA OBTENER AHORRO ENERGÉTICO EN LOS ACTUADORES DE LA PLATAFORMA STEWART-GOUGH

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Resumen: Este artículo se enfoca en la aplicación de los modelos dinámicos y estáticos del robot paralelo de Stewart-Gough usando el procedimiento de Newton-Euler y la reciprocidad de la teoría de Screw, estas se utilizan para encontrar la fuerza en cada actuador de la pierna en determinada tarea. Luego el algoritmo implementado y validado por medio de simulación asistida por computadora. Por otro lado, el algoritmo PSO (Optimización por Enjambre de Partículas) se implementa para encontrar la mejor posición del robot con respecto a una rotación de la plataforma base en el eje Z, con el objetivo de obtener la fuerza mínima posible en el actuador para la tarea del robot.

Palabras clave: Robots paralelos, Modelo Dinámico, Validación Numérica, Optimización.

Abstract: This paper focusses in the application of the Stewart-Gough parallel robot dynamic and static models using the Newton-Euler procedure and reciprocity from screw theory, this is used for to find the force in each leg actuator in a determinate task. Then the algorithm implemented and validated through of a simulation aided for computer. On the other hands, the PSO (Particles Swarm Optimization) algorithm is implemented for find the best robot position with respect to a base platform rotation in the Z-axis, aiming at obtaining the minimum force possible in the actuator for the robot task.

Keywords: Parallel Robots, Dynamic Model, Numerical Validation, Optimization.

INTRODUCTION

The most significant current discussion in the mechanism movement nowadays is the deliberate use of energy, the purpose of this paper is put together several parallel robot characteristics for development an energetic save up method through the robot parameters optimization.

According to (Merlet, 2005) a parallel robot can be defined as a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains, on the other hand (Tsai, 1999) define the parallel manipulators as a kinematic structure form by two platforms connected by mean of at least two open-loop chain, furthermore, define the general parallel manipulator characteristics as higher payload capacity and higher displacement velocities, etc.

For parallel robot use in different applications of aeronautics (Asif, 2012) is necessary to apply the robot dynamic model for seeing the different forces and elements that affect the movement when performing a determinate trajectory task, in the (Amir Ghobakhloo M. Eghtesad, 2006; Jayakrishna, Dist, State, Babu, & State, 2015; Kalani, Rezaei, & Akbarzadeh, 2016; Lopes, 2009; Merlet, 2005; Tsai, 1999) is presented a dynamic model synthesis for Stewart-Gough platform applying reciprocity from screw theory, the virtual work principle and Euler-Newton procedure.

Applied for serial robots (Mohammed, Schmidt, Wang, & Gao, 2014) present a study on energy consumption for performing a task this system is designed to choose the joint configuration that requires the lowest energy sense. The (Paes, Dewulf, Vander Elst, Kellens, & Slaets, 2014) development a research on the different way of realizing a pick and place task, where shortest-distance and energy-optimal trajectories are compared for getting the minimum power consumption on the first three robot joints. The (Paryanto, Brossog, Bornschlegl, & Franke, 2015) is presented a research on energetic consumption and most main features based on investigation results aiming to improve the efficiency of industrials robots used in manufacturing systems, following the same idea (Paryanto et al., 2014) use an industrial robot dynamic model for validate with a real robot and energetic used incidence when extern payload is applied under several operating conditions.

Aim to encounter the better trajectory task using the kinematic model and artificial vision (Ríos, J. G., Oviedo, E. M., & Cortés, 2013) make a simulation of 3 Degrees of Freedom robot for mathematical validation. Actually are implemented hybrid robots for optimization of several tasks, (Peña, Aracil, & Saltarén, 2008) using the optimization theory for limbs length calculation and select the better position and orientation for a suitable workspace.

For to reduce the energy sense in the industrial multi-robot systems is implemented an algorithm that put together and establishes the minimizing joints trajectories and changing the operation sequences for an energetic save-up to 45% (Riazi, Bengtsson, Wigstrom, Vidarsson, & Lennartson, 2015), however (Verscheure, Demeulenaere, Swevers, Schutter, & Diehl, 2008) focuses on algorithm optimization for time-optimal path and time-optimality versus energy-optimality for industrial robot trajectory task.

This paper begins in the chapter 2 will examine a Stewart-Gough modeling description for position and orientation analysis, the chapter 3 describe the Stewart-Gough dynamic model, then in the chapter 4 is described the PSO (Particles Swarm Optimization) algorithm for force save-up optimization, in the chapter 5 is presented the results obtained through the numerical simulation and finally is presented the paper conclusions.

2. STEWART-GOUGH PLATFORM MODELING

The Stewart-Gough platform, from now on S-G platform, is generally understood as a six degrees-of-freedom manipulator. This mechanism shown in the fig. 1 it is constituted of six extensible legs, this extensible legs may be understood as the prismatic joint that generates the moving for each articulation, furthermore, each leg is conformed by an universal joint and a spherical joint connected to fixed and a moving platform.

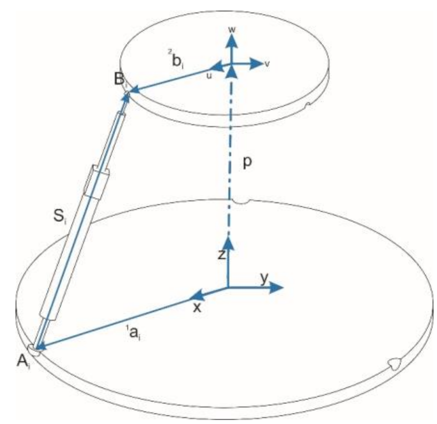

Fig. 1. Position analysis representation in the S-G platform.

For the proposed analysis, three coordinates systems O_1, O_2 and O_3 are fixed, the first frame O_1 (x, y, z) is located at the centroid, O on the fixed base, the second frame O_2 (u, v, w) is located at the centroid, P of the moving platform, the frame O_3 (x_i, y_i, z_i) is located in each limb with it is origin in the *ith* point A_i, the z_i-axis is located in direction from A_i to B_i. The y_i-axis is parallel to the cross product of two unit vectors along the z_i and z axis, and the x_i-axis is defined by the right-hand rule.

The non-actuated universal joint at point A_i and spherical joint at point B_i are contained in the frames $x - y$ and $u - v$ respectively and can be defined two positions vectors, the first vector b_i presented in the equation (1) described the B_i position on the moving frame and second vector a_i described the A_i position on the fixed frame, this may be seen too as,

$$a_i = \begin{vmatrix} Rcos(\theta_i) \\ Rsin(\theta_i) \\ 0 \end{vmatrix}, {}^2b_i = \begin{vmatrix} rcos(\theta_i + \theta_o) \\ rsin(\theta_i + \theta_o) \\ 0 \end{vmatrix}; \quad i = 1 \quad to \quad 3. \tag{1}$$

Where $\Theta_0 = 60°$ due to the symmetrical configuration, on the other hand, the vector P (equation 2) of the figure described the moving center platform location with respect to the fixed frame and can be written as,

$$P = \begin{bmatrix} x & y & z \end{bmatrix} \tag{2}$$

For getting completely the location is used the Three Euler-Angles method for describing the moving platform orientation, this is represented by a ψ angle through of a rotation on the Z-axis, followed by a second rotation of an angle Θ through of X'-axis, and finally is applied a third rotation with value ϕ on Z''-axis, this is presented in the equation (3) of way summarized.

$${}^1R_2 = \begin{bmatrix} c\phi c\theta c\psi - s\phi s\psi & -c\phi c\theta s\psi - s\phi c\psi & c\phi s\theta \\ s\phi c\theta c\psi + c\phi s\psi & -s\phi c\theta s\psi + c\phi c\psi & s\phi s\theta \\ -s\theta c\psi & s\theta s\psi & c\theta \end{bmatrix} \tag{3}$$

Now applying the Screw theory found in more detail in (Tsai, 1999) is possible to express the spatial body generalized position and orientation through the infinitesimal displacement as a translational and a rotation about a unique axis, this theory is an important mathematical tool commonly used in the parallel robot general analysis and is presented in the equation (6), this is represented by two three dimensional vector shown in the equation (4).

$$\hat{\$} = \begin{bmatrix} s \\ s_o \times s + \lambda s \end{bmatrix} \tag{4}$$

Explained by (Tsai, 1999) in the equation (4) S is the unit vector along the screw axis and S_0 is a point in the space represented as three coordinates between the origin frame and any point on the screw axis, the cross product $S_0 \times S$, in this case, is defined as the screw axis geometric moment about the origin reference frame. For defined completely the Screw the λ term is the relation between the linear and angular displacements $\lambda = d/\Theta$, this means that for a prismatic joint λ is zero, and for a revolute joint λ is infinite. However, is non-possible define completely without specify the screw axis amplitude also known as the intensity, the screw may be written as in the equation (5),

$$\$ = \dot{q}\hat{\$} \tag{5}$$

The screws present on each leg can be written as equation (6),

$$\$_p = \sum_{i=1}^{n} \dot{q}\hat{\$} \tag{6}$$

This is possible due to the equation (6) that described the end effector resulting motion and is written as the equation (7),

$$\$_p = \dot{\theta}_{(1,i)}\hat{\$}_{1,i} + \dot{\theta}_{(2,i)}\hat{\$}_{2,i} + \dot{d}_{(3,i)}\hat{\$}_{3,i} + \dot{\theta}_{(4,i)}\hat{\$}_{4,i} + \dot{\theta}_{(5,i)}\hat{\$}_{5,i} + \dot{\theta}_{(6,i)}\hat{\$}_{6,i} \tag{7}$$

Where the intensity is presented in the equation (8),

$$\dot{q} = \begin{cases} \dot{\theta} & for\ revolute\ joint \\ \dot{d} & for\ prismatic\ joint \end{cases} \tag{8}$$

On the other hand, the reciprocity based in screw theory defined the robot actuated joints and represented in the equation (9) as,

$$\hat{\$}_r = \begin{bmatrix} s_r \\ s_{ro} \times s_r + \lambda s_r \end{bmatrix} \tag{9}$$

Where λ_r is defined as the moment ratio to the force, similar to the screw pitch, i.e. for a pure moment $\lambda_r = \infty$ and for a pure force $\lambda_r = 0$, due to that the unique actuated joint is the prismatic to pre-multiply the equation (8) by the reciprocal screw transpose remains the equation (10),

$$\hat{\$}^T_{r,i}\$_p = \hat{\$}^T_{r,i}\hat{\$}_{3,i}\dot{d}_{(3,i)} \tag{10}$$

In the parallel robots, the analysis is done for six legs simultaneously, the equation (11) can be expanded as a symmetric matrix that gets the result in all joints at the same time, this is seen below as,

$$\begin{bmatrix} s_{ro,1} \times s_{r,1} & s_{r,1} \\ \vdots & \vdots \\ s_{ro,6} \times s_{r,6} & s_{r,6} \end{bmatrix} \$_p = \begin{bmatrix} I_{6\times 6} \end{bmatrix} \begin{bmatrix} \dot{d}_{(3,1)} \\ \vdots \\ \dot{d}_{(3,6)} \end{bmatrix} \tag{11}$$

The equation (11) the reciprocal screw can also be represented as a Jacobian when is applied a vector composed by the angular and linear velocities, this can be re-written in the equation (12) as,

$$J_x\left[\dot{x}\right]=J_q\left[\dot{d}\right] \tag{12}$$

Where,

$$\dot{x}= \begin{bmatrix} w_p \\ v_o \end{bmatrix},$$

J_x and J_q are the Jacobians related to the inverse and direct kinematic and followed the orthogonal relation $J= J_x^{-1}J_q$ and d is a displacement vector resultant for each leg.

So is possible to write the relation S_r of the equation (11) as,

$$s_r = \frac{p+bi - ai}{\|AB_i\|} \tag{13}$$

Where,

$$\|AB_i\|=|p+bi - ai|$$

And $b_i={}^1R_2{}^2b_i$ and a_i denote the spherical and universal joints positions respect the fixed frame in the *ith* leg.

3. S-G PLATFORM DYNAMIC

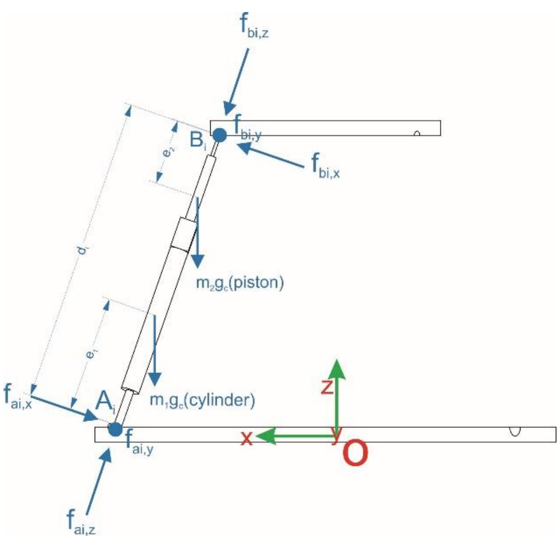

Fig. 2. The legs reaction and mass center location.

After solving the robot kinematic problem is presented the dynamic analysis, but according to (Tsai, 1999) is possible to represent this analysis of three different ways, the Lagrangian, the virtual work and the Euler-Newton formulations, the latter is implemented in this work, so is presented a summarized on the dynamic having a more complete analysis in (Merlet, 2005; Tsai, 1999).

For position analysis is used the equation (13) to find each leg position, now assuming the joint connection with the moving and base platforms in the figure (2) is described the i^{th} limb orientation with respect to the fixed platform based in two Euler angles terms ϕ and ϴ about the axes z and y', the ith limb rotation matrix can be written in the equation (15) as,

$${}^AR_i = \begin{bmatrix} c\phi_i c\theta_i & -s\phi_i & c\phi_i s\theta_i \\ s\phi_i c\theta_i & c\phi_i & s\phi_i s\theta_i \\ -s\theta_i & 0 & c\theta_i \end{bmatrix} \tag{15}$$

Where the unit vector S_i expressed in the *ith* limb frame is given by,

$${}^is_i = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{16}$$

Then is obtained multiplying the equation (15) with equation (16) $s_i = {}^AR_i{}^is_i$, that is the unit vector expressed in matrix function orientation components of the equation (17),

$$\begin{aligned} &to \\ &c\theta_i = s_{iz}, \\ &s\theta_i = \sqrt{s_{ix}^2 + s_{iy}^2} \quad (0\leq\theta\leq\pi), \\ &s\phi_i = s_{iy}/s\theta_i, \\ &c\phi_i = s_{ix}/s\theta_i \end{aligned} \tag{17}$$

In the physical parameters, the *ith* limb center mass of the figure 2 may be located through of the equation (18) and (19),

$$\mathrm{r}_{1i} = a_i + e_1 s_i \tag{18}$$

And

$$r_{2i} = a_i + (d_i - e_2)s_i \tag{19}$$

The centroid velocity and acceleration *P* is obtained when is derivate the position the equation (2) with respect to time, so the moving platform angular velocity ω_p can be written as the equation (20) in Euler angles and the body-fixed w, v and w terms,

$$w_p = \begin{bmatrix} \dot{\psi}c\phi s\theta - \dot{\theta}s\phi \\ \dot{\psi}s\phi s\theta + \dot{\theta}c\phi \\ \dot{\psi}c\theta + \dot{\phi} \end{bmatrix} \tag{20}$$

And the angular acceleration of equation (21),

$$\dot{w}_p = \begin{bmatrix} \ddot{\psi}c\phi s\theta - \dot{\psi}\dot{\phi}s\phi s\theta + \dot{\psi}\dot{\theta}c\phi c\theta - \ddot{\theta}s\phi - \dot{\theta}\dot{\phi}c\phi \\ \ddot{\psi}s\phi s\theta + \dot{\psi}\dot{\phi}c\phi s\theta + \dot{\psi}\dot{\theta}s\phi c\theta + \ddot{\theta}c\phi \quad \dot{\theta}\dot{\phi}s\phi \\ \ddot{\psi}c\theta - \dot{\psi}\dot{\theta}s\theta + \ddot{\phi} \end{bmatrix} \tag{21}$$

The velocities and accelerations *ith* limbs in the mass center may be found deriving the equation (21) and equation (22) with respect to time, (Tsai, 1999) defined the reaction forces in the equation (22) and (23) for each leg as,

$$^{i}f_{bix} = \frac{1}{d_i}[m_1e_1g_cs\theta_i + m_2(d_i - e_2)g_cs\theta_i - m_1e_1{}^{i}\dot{v}_{1ix} - m_2(d_i - e_2){}^{i}\dot{v}_{2ix} - I_{1iy}{}^{i}\dot{\omega}_{iy} - I_{2iy}{}^{i}\dot{\omega}_{iy}] \tag{22}$$

And,

$$^{i}f_{biy} = \frac{1}{d_i}\left[-m_1e_1{}^{i}\dot{v}_{1iy} + m_2(d_i - e_2){}^{i}\dot{v}_{2iy} + I_{1ix}i\dot{\omega}_{ix} + I_{2ix}i\dot{\omega}_{ix}\right] \tag{23}$$

Writing the newton equation (24) for the moving platform expressed in the fixed frame and the resulting moment equation expressed in the moving platform as,

$$\sum_{i=1}^{6} {}^{A}f_{bi} + m_p {}^{A}g = m_p {}^{A}\dot{v}_b \tag{24}$$

This result in the moment equation is the equation (25),

$$^{B}n_p = \sum_{i=1}^{6} {}^{B}b_i \times {}^{B}f_{bi} \tag{25}$$

Hence the equations (24) and (25) constitute a six linear equations and a system of six unknowns that can be easily be solve for f_{bz}.

Then it is assumed that all forces act on the i^{th} piston along the *z*-axis getting the actuation τ_i force in the equation (26) as,

$$\tau_i = {}^{i}f_{biz} + m_2g_cc\theta_i + m_2{}^{i}\dot{v}_{biz} \tag{26}$$

4. OPTIMIZATION PERFORM BY PSO

The heuristic algorithm presented in (Singiresu S. Rao, 2009) and based on Particles Swarm Optimization and abbreviated PSO is a systematic model that recreate the insets swarm behaviors i.e. their behavior when is applicate a random characteristic as position and velocity, this allows that this particles can travel by all space design and remember the best position they were in. Actually most optimization has been development for performance complex engineering problems, (Riaño, C., Cortés, C. P., & García, 2014) development a three degrees of freedom and is used genetic algorithms getting the biggest robot workspace for task performance. The information shared between each particle for adjust their individual position and velocities based on the best information received.

For minimize the force on the actuator is implemented in the equations and constraint,

$$\begin{aligned} &Minimize \quad f(x) \\ &subjetc\ to: \\ &g_i \leq 0 \\ &xlb \leq x \leq xub \end{aligned} \tag{27}$$

Where the term g_i is the *ith* constraint, *xlb* and *xub* are the *x* variable lower and upper boundaries limits. Then for proposed problem in this work this values reals for equation (27) are determinates in the equation (28),

$$\begin{aligned} &Mimize \quad f(x) = max(\tau_i), \\ &subjetc\ to: \\ &g_1 = 0.5 - direc \leq 0, \\ &g_2 = 73mm - lmin \leq 0, \\ &g_2 = lmax - 142mm \leq 0, \\ &0 \leq x \leq 10, \end{aligned} \tag{28}$$

Where *direc* is the work index and is defined in the equation (29) as,

$$direc = \frac{1}{\lambda_{max}} \tag{29}$$

The λ_{max} is the matrix *G* higher eigenvalue defined as,

$$G = M^{-1}D \tag{30}$$

In the equation (30) M is the gramminian matrix related with the screw (equation 31),

$$M = \sum_{i=1}^{6} \$_i \$_i^T \quad (31)$$

And D is defined by the equation (32),

$$D = \begin{bmatrix} I(3{,}3) & 0 \\ 0 & 0_{6,6} \end{bmatrix} \quad (32)$$

5. NUMERICAL SIMULATION

This chapter aiming to get the minimum energy consume to perform a given task in the 3-D space following a trajectory interpolated through of a third-order (3°) Spline between an initial and a final location.

In a previously developed work was found that optimal base platform radius must be at least 2 times larger than the moving platform radius, also was corroborated through of a software CAD-CAE, getting a minimum percentage error between analytical and simulated dynamics models.

This work compared the different S-G dynamic analytical for four *z*-axis rotation: zero degrees, minimum degree, mean degree and maximum degree find for PSO algorithm, determining the minimum actuator force exerted on that journey on the angle evaluated.

The robot parameters are shown in the table 1, these parameters are implemented for both methods between the initial point $P_i = [0, -0.0003, 0.09, 0, 0, 0]$ and a final point $P_f = [0, 0.003, 0.09, 30, 0, 0]$ where the first three data are values of displacements in meters and the others three values are angles in degrees for the rotation.

Table 1. Robot parameters.

Parameter	Value	Parameter	Value
r_B [mm]	750.0	I_{MXX} [kg/mm^2]	60.87586
r_M [mm]	375.0	I_{MYY} [kg/mm^2]	760.87586
		I_{MZZ} [kg/mm^2]	121.03446
m_M [kg]	0.17222	I_{CXX} [kg/mm^2]	0.730262
m_C [kg]	0.0018763	I_{CYY} [kg/mm^2]	0.7730261
m_P [kg]	0.0005456	I_{CZZ} [kg/mm^2]	0.008719
		I_{PXX} [kg/mm^2]	0.215487
e_1 [mm]	43.874	I_{PYY} [kg/mm^2]	0.215483
e_2 [mm]	37.791	I_{PZZ} [kg/mm^2]	0.000722

Where,

- r_B and r_M are a base and moving platforms radius respectively.
- m is a moving platform (M), cylinder (C) and piston (P) mass.
- I is an inertial moment in the three axis from moving platform (M), cylinder (C) and piston (P).

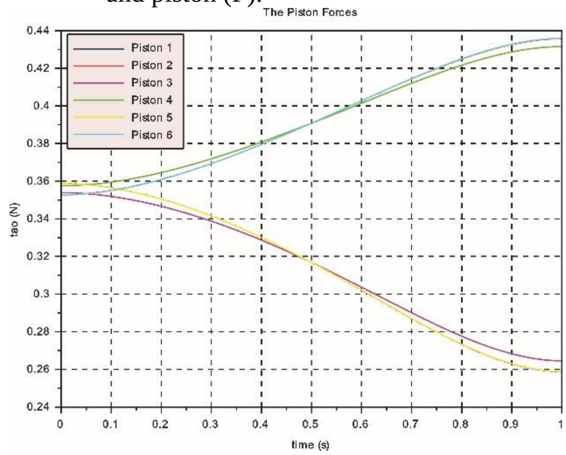

Fig. 3. Force in each robot leg for zero Z-angle rotation.

The force in the graphics of the figures 3 and 4 represent the variation in the angles achieved by the PSO algorithm for zero and maximum angle obtained.

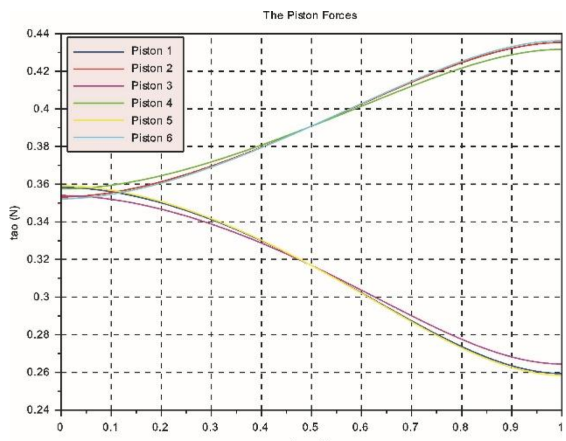

Fig. 4. Force in each robot leg for maximum Z-angle rotation.

In the figure 4 shown the force exerted in each robot actuator for a Z-axis rotation of 9.3386487°, the difference is in the piston 2 that decreases its value comparing with the same piston for zero rotation.

6. CONCLUSIONS

The angles found for that the base platform has the biggest workspace around the Z-axis allow minimizing the action force exerted interval in the motors for performing the same task applying a lower force.

This result has a higher incidence in the electric actuator selection aiming at obtaining a lower energy consumption and demonstrating the importance of this type of analysis for saved energy.

This paper presents the results to a versatile method that works for a great number of robots, changing alone some slows shape parameters and yours kinematic and dynamic models.

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