DYNAMIC MODELING OF A 6-DOF PARALLEL STRUCTURE DESTINATED TO HELICOPTER FLIGHT SIMULATION

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Abstract: The dynamic analysis is the basic element of the mechanical design and control of parallel mechanisms. The parallel robots dynamics requires a great deal of computing as regards the formulation of the generally nonlinear equations of motion and their solution. In this paper a solution for solving the dynamical model of a 6-DOF parallel structure destined to helicopter flight simulation is presented. The obtained dynamical algorithms, based on the kinematical ones, offer the possibility of a complex study for this type of parallel structure in order to evaluate the dynamic capabilities and to generate the control algorithms.

1 INTRODUCTION

Parallel robots have some advantages over serial ones such as higher stiffness, very good precision, high speeds and accelerations, a better weight over payload rate. However, kinematic and dynamic analysis of the parallel structures is much more complicated due to the constraints and singularities presence. Dynamic effects and their analysis are the basis of design specifications and advanced control of the parallel mechanical systems.

Many of the mechanics classical methods cannot be successfully applied for parallel robots.

There are essentially four methods:

1. Newton-Euler equations with impulse and momentum formulation or the D'Alembert equations;
2. Lagrange equations of first kinds with so-called Lagrange multipliers;
3. Lagrange equations of second kind with a minimum number of system coordinates;
4. Virtual work formulation including inertia forces.

In (Pierrot, 1990), a simplified method of determining the dynamic model of the HEXA robot in two steps is proposed.

(Codourey, 1991) proposes the first dynamic model that can be used to control the parallel DELTA robot in real time.

(Guglielmetti, 1994) presents the inverse dynamic model for the DELTA robot in the analytical form using the Newton's laws.

(Honneger, 1997) suggested the use of the dynamic equations in an adaptive control scheme for the Hexaglide robot, in which the pursuance errors are used on-line to correct the parameters used in dynamic equations.

(Stamper, 1998) present a dynamical model for a parallel structure with three degrees of freedom. This model was also generated with the simplications of the Codourey model.

(Tsai, 1999) present a dynamical model for a parallel structure with three degrees of freedom, using the virtual principle.

(Miller, 1992) presents the complete dynamic model of the DELTA robot based on Lagrange equations. In this case one considers that the robot bars possess inertia moments themselves.

To solve the dynamic model, (Merlet, 2000) uses Lagrange formulas. He has applied the direct and the inverse dynamic model for the *"left hand"*, to a prototype accomplished at INRIA based on a KPS kinematic chain structure.

(Pisla, 2000) propose a generalized dynamic model for parallel robots using first order Lagrange equations on the basis of equivalent masses.

(Guégan, 2002) presents a new solution for the dynamic model for the Orthoglide with Newton-Euler equations.

(Itul, 2003 and 2006) present a comparative study among various dynamical methods and

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different solutions for solving the dynamical model for the guided in three points parallel robots.

Generally, in the above mentioned contributions, the experimental identification of dynamics for the parallel robots is restricted to simple models in combination with adaptive control algorithms.

Flight simulators are extensively used by the aviation industry and the military for pilot training, disaster simulation and aircraft development. The different types of flight simulators range from video games up to full-size cockpit replicas mounted on hydraulic, electric or electromechanical actuators (Nahon, 2000), (Andreev, 2000).

Contrary to popular belief, flight simulators are not used to train pilots how to fly aircraft. Today's modern simulators are used by commercial airlines and the military alike, to familiarize flight crews in normal and emergency operating procedures. Using simulators, pilots are able to train for situations that they are unable to safely do in actual aircraft. These situations include loss of flight surfaces and complete power loss etc. In all cases **dynamics** plays a very important role for the behaviour of parallel structures used as flight simulators.

It is widely acknowledged that the cues provided by a good visual system offer the bulk of realism in a flight simulator. It has also been shown that pilots consider the provision of consistent motion cues to add substantially to the realism of the simulation and to be helpful in the piloting task (Reid, 1988).

Thus, motion platforms are used on modern high-end flight simulators in order to provide motion cues consistent with the visual, auditory and control-feel cues to which the pilot is also subjected.

Within the motion-related subsystems, the most consistent research effort is over the washout subsystem which takes the motions generated by the aircraft equations including large displacements and filters to provide simulator motion-base commands. These commands must provide the pilot with realistic motion cues, while remaining within the simulator's motion limits (Nahon, 2000).

The paper is organized as follows:

Section 2 is dedicated to the description of the studied 6-DOF parallel structure;

Section 3 deals with the dynamic modeling using the virtual work principle;

Section 4 presents some simulations tests on a parallel robot;

The conclusions of this work are detailed in the section 5.

2 DESCRIPTION OF THE 6-DOF PARALLEL STRUCTURE

Taking into consideration the imposed requirements for a flight simulator, which should have 6-DOF, it was chosen the family of type Stewart-Gough parallel structures (Figure 1).

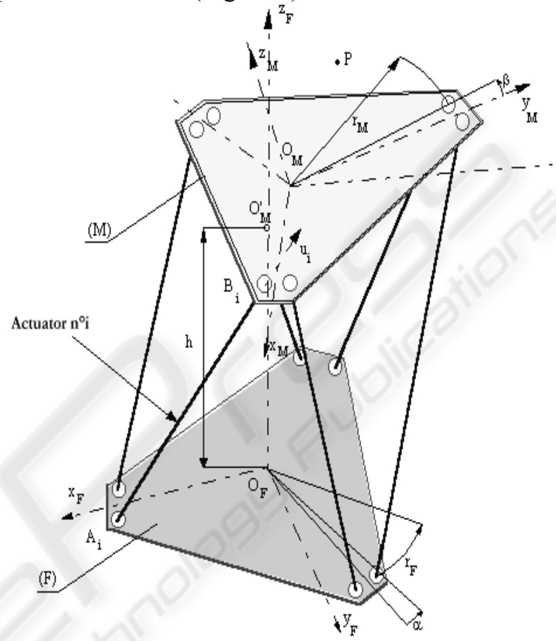

Figure 1: The 6-DOF parallel structure.

Generally, these parallel structures consist of six mobile arms, connected to the base and mobile platform through universal joints located at each end of the arm.

The mobile platform materializes the end element (end-effector). These kind of parallel structures are characterized by a robust mechanical structure and a high dynamic performance, a good ratio between the manipulated mass and the own mass.

The main difficulty results from the complexity in the motion control. Thus, the dynamics and its simulation is an important stage in order to test the capabilities of the robot and to develop the adequate control system.

2.1 Structural Considerations

For parallel mechanisms of F family the number of degrees of mobility is calculated with formula (Plitea, 2005):

$$M = (6-F)N - (5-F)C_5 - (4-F)C_4 - \\ -(3-F)C_3 - (2-F)C_2 - (1-F)C_1 \qquad (1)$$

where:
M - mobility degree of the mechanism; F - mechanism family - the number of common constraints for all mechanism elements; N - number of mobile elements; C_i - number of "i" class joints; k = number of kinematic chains which connect the mobile platform to the base; n - number of elements of a kinematic chain for platform guidance for symmetric structures; c_i - number of "i" class joints of a kinematic chain for platform guidance.

The parallel robot mechanism family is:

$$F = 0 \qquad (2)$$

In our case:

$$N = 13; \; C_5 = 6; \; C_3 = 12; \qquad (3)$$

The mobility degree of the parallel mechanism will be:

$$M = 6N - 5C_5 - 3C_3 \\ M = 6 \qquad (4)$$

2.2 Kinematic Modeling

In the case of inverse geometric problem, the actuation displacements are obtained with respect to the position and orientation of the mobile platform. An analytical solution could be obtained and applied in the control algorithms. For solving the inverse geometric problem, the transformation matrices method was used, using the Euler angles. The model has been already presented in (Pisla, 2007).

In the case of direct geometric problem the position and orientation of the mobile plate is calculated with respect to the actuation displacements. For solving the inverse geometric problem the transformation matrices method was used, using the Euler angles. The solution is a numerical one and the obtained nonlinear system could be computed by means of Newton-Raphson method (Pisla, 2007). The singularities of this paralle structure have been extensively discussed in (Pernkopf, 2002).

3 DYNAMIC MODELING OF THE 6 DOF PARALLEL ROBOT

The inverse dynamics consists in finding the relationships between the actuating joint forces τ_i, (i=1,2,…,6) and the motion laws for the manipulated object.

To study the dynamics, several simplifying hypotheses were adopted in the model:

-all joints are frictionless;

-the masses of guiding arms A_iC_i are neglected;

In Figure 2 the geometric parameters, the corresponding system coordinates and the forces are represented.

The used notations in the model are:

R_B - radius of fixed base; e_B, d_B - geometric parameters on the base; $\lambda_1 = \lambda_2 = 0$; $\lambda_3 = \lambda_4 = 120^0$; $\lambda_5 = \lambda_6 = -120^0$; r_p - radius of the working platform (WP); e_p, d_p - geometric parameters on the working platform; $\delta_1 = \delta_2 = 0^0$; $\delta_3 = \delta_4 = 120^0$; $\delta_5 = \delta_6 = -120^0$; m_p - mass of the working platform + the helicopter;

C = mass centre for the working platform + the helicopter; $C_{x'}$,$C_{y'}$,$C_{z'}$ - main central inertia axes; $I_{x'}$,$I_{y'}$,$I_{z'}$ - main inertia moments; oxyz - coordinate system of the mobile platform; OXYZ - fixed reference coordinate system; $OX_i'Y_i'Z_i'$ - coordinate system rotated with the angle λ_i with respect to the OXYZ system around the Z axis; $ox_iy_iz_i$ - coordinate system rotated with the angle δ_i with respect to the oxyz system around the z axis;
CXY'Z' - mobile reference system; its axes are parallel with the fixed coordinate system OXYZ axes; x_c, y_c, z_c - the coordinates of the mass centre C with respect to the oxyz system; X_c, Y_c, Z_c = the coordinates of the mass centre C with respect to the OXYZ fixed system of the robot.

In the inverse dynamic model, the input data are:

$$x_C = x_C(t), \;\; y_C = y_C(t), \;\; z_C = x_C(t), \\ \psi = \psi(t), \;\; \theta = \theta(t), \;\; \varphi = \varphi(t)$$

The actuation forces should be computed.

$$\tau_1 = \tau_1(t), \;\; \tau_2 = \tau_2(t), \;\; \tau_3 = \tau_3(t), \\ \tau_4 = \tau_4(t), \;\; \tau_5 = \tau_5(t), \;\; \tau_6 = \tau_6(t)$$

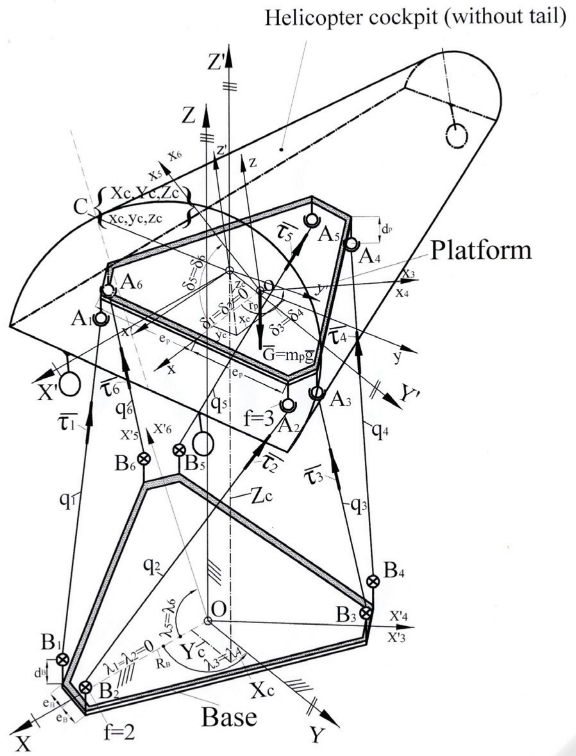

Figure 2: Dynamic modeling of the parallel robot.

The algorithm for solving the inverse dynamic model is presented as follows.

$$e_{Bi} = (-1)^i e_B , \qquad i = 1,2,....,6 \tag{5}$$

The coordinates of B_i points with respect to the $OX_i'Y_i'Z_i'$ are:

$$X'_{Bi} = R_B,\ Y'_{Bi} = e_{Bi},\ Z'_{Bi} = d_B,\ i = 1,2,...,6 \tag{6}$$

The coordinates of B_i points with respect to the OXYZ are:

$$\begin{bmatrix} X_{Bi} \\ Y_{Bi} \\ Z_{Bi} \end{bmatrix} = \begin{bmatrix} C\lambda_i & -S\lambda_i & 0 \\ S\lambda_i & C\lambda_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X'_{Bi} \\ Y'_{Bi} \\ Z'_{Bi} \end{bmatrix},\ i = 1,2,...,6 \tag{7}$$

$$e_{pi} = (-1)^{i-1} e_p , \quad i = 1,2,...,6 \tag{8}$$

$$x'_{Ai} = r_p, \quad y'_{Ai} = e_{pi},\ z'_{Ai} = -d_p , \quad i = 1,2,...,6 \tag{9}$$

The coordinates of A_i points with respect to the $ox_i y_i z_i$ are:

$$\begin{bmatrix} x_{Ai} \\ y_{Ai} \\ z_{Ai} \end{bmatrix} = \begin{bmatrix} c\delta_i & -s\delta_i & 0 \\ s\delta_i & c\delta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x'_{Ai} \\ y'_{Ai} \\ z'_{Ai} \end{bmatrix}, \quad i = 1,2,...,6 \tag{10}$$

The coordinates of A_i points with respect to the OXYZ are:

$$\begin{bmatrix} X_{Ai} \\ Y_{Ai} \\ Z_{Ai} \end{bmatrix} = \begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} + \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_1 & \beta_2 & \beta_3 \\ \gamma_1 & \gamma_2 & \gamma_3 \end{bmatrix} \begin{bmatrix} x_{Ai} - x_C \\ y_{Ai} - y_C \\ z_{Ai} - z_C \end{bmatrix}, \quad i = 1,2,...,6 \tag{11}$$

Using the relations (7) and (11) the joint coordinates are:

$$q_i = \sqrt{(X_{Ai} - X_{Bi})^2 + (Y_{Ai} - Y_{Bi})^2 + (Z_{Ai} - Z_{Bi})^2}, \quad i = 1,2,...,6 \tag{12}$$

We consider the rotations around the CX', CY', CZ' axes (axes parallel with the fix ones OX, OY, OZ):

(13)

A_1=CθCφ	A_2=-Sφ	A_3=0
B_1= CθSφ	B_2= Cφ	B_3=0
C_1=-Sθ	C_2=0	C_3=1

Then, the angular speed $\overline{\omega}$ and the angular acceleration $\overline{\varepsilon}$ of the mobile platform may be determined with the following relations:

$$\begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} = \begin{bmatrix} A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \\ C_1 & C_2 & C_3 \end{bmatrix} \begin{bmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \varepsilon_Z \end{bmatrix} = \begin{bmatrix} A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \\ C_1 & C_2 & C_3 \end{bmatrix} \begin{bmatrix} \ddot{\psi} \\ \ddot{\theta} \\ \ddot{\varphi} \end{bmatrix} + \begin{bmatrix} \dot{A}_1 & \dot{A}_2 & \dot{A}_3 \\ \dot{B}_1 & \dot{B}_2 & \dot{B}_3 \\ \dot{C}_1 & \dot{C}_2 & \dot{C}_3 \end{bmatrix} \begin{bmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} \tag{15}$$

For the rotations around the fix axes CX', CY', CZ' the corresponding cosines may be determined using the following equations:

$$\begin{array}{lll} \alpha_1 = c\theta c\varphi & \alpha_2 = -c\psi s\varphi + s\psi s\theta c\varphi & \alpha_3 = s\psi s\varphi + c\psi s\theta c\varphi \\ \beta_1 = c\theta s\varphi & \beta_2 = -c\psi c\varphi + s\psi s\theta s\varphi & \beta_3 = -s\psi c\varphi + c\psi s\theta s\varphi \\ \gamma_1 = -s\theta & \gamma_2 = s\Psi c\theta & \gamma_3 = c\Psi c\theta \end{array} \tag{16}$$

The inertia moments are:

$$\begin{cases} I_{X'} = I_X \alpha_1^2 + I_Y \alpha_2^2 + I_Z \alpha_3^2 \\ I_{Y'} = I_X \beta_1^2 + I_Y \beta_2^2 + I_Z \beta_3^2 \\ I_{Z'} = I_X \gamma_1^2 + I_Y \gamma_2^2 + I_Z \gamma_3^2 \\ I_{X'Y'} = I_{Y'X'} = -I_x \alpha_1 \beta_1 - I_y \alpha_2 \beta_2 - I_z \alpha_3 \beta_3 \\ I_{Y'Z'} = I_{Z'Y'} = -I_x \beta_1 \gamma_1 - I_y \beta_2 \gamma_2 - I_z \beta_3 \gamma_3 \\ I_{Z'X'} = I_{X'Z'} = -I_x \gamma_1 \alpha_1 - I_y \gamma_2 \alpha_2 - I_z \gamma_3 \alpha_3 \end{cases} \tag{17}$$

Then, the actuation forces τ_i are obtained:

$$\left(I_P^T\right)^{-1}\left\{M\ddot{X}_P + C\dot{X}_P + T_C^g\right\} = \tau \tag{18}$$

where

$$I_P^T = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \tag{19}$$

$$M = \begin{bmatrix} m_p & 0 & 0 & 0 & 0 & 0 \\ 0 & m_p & 0 & 0 & 0 & 0 \\ 0 & 0 & m_p & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{11} & a_{12} & a_{13} \\ 0 & 0 & 0 & a_{21} & a_{22} & a_{23} \\ 0 & 0 & 0 & a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{20}$$

$$\ddot{X}_p = \begin{bmatrix} \ddot{X}_C \\ \ddot{Y}_C \\ \ddot{Z}_C \\ \ddot{\Psi} \\ \ddot{\theta} \\ \ddot{\varphi} \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{11} & b_{12} & b_{13} \\ 0 & 0 & 0 & b_{21} & b_{22} & b_{23} \\ 0 & 0 & 0 & b_{31} & b_{32} & b_{33} \end{bmatrix} \tag{21}$$

$$\dot{X}_P = \begin{bmatrix} \dot{X}_C \\ \dot{Y}_C \\ \dot{Z}_C \\ \dot{\Psi} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} \quad T_g^C = \begin{bmatrix} 0 \\ 0 \\ -m_p g \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{bmatrix} \tag{22}$$

In (19)-(21): $a_{11}, \cdots, a_{33}$ depend on the platform inertia moments $I_{X'}, I_{Y'} I_{Z'} I_{X'Y'} I_{Y'Z'} I_{Z'X'}$ and A_i, B_i, C_i $i = 1..3$; $b_{11}, \cdots, b_{33}$ depend on the platform inertia moments $I_{X'}, I_{Y'} I_{Z'} I_{X'Y'} I_{Y'Z'} I_{Z'X'}$ and $\dot{A}_i, \dot{B}_i, \dot{C}_i$ $i = 1..3$; $C_{11}, \cdots, C_{66}$ depend on the direction cosines for the platform, the coordinates of points A_i $i = 1..6$ and the coordinates of the platform mass center C_i $i = 1..6$.

4 SIMULATION TESTS

The achieved kinematic and dynamic algorithms have been implemented in the developed simulation system (Pisla, 2005), (Pisla, 2007). It consists of five main modules: Kinematics; Singularities; Workspace; Trajectory, Dynamics. Within the simulation system the virtual graphical model was created, the 3D functional model allows the designer to understand its functionality (Figure 3).

The geometric parameters can be modified within the 3D modeling software influencing the simulation environment. The assembly relations between the parts, subassemblies and between parts and subassemblies can be also modified. These facilities enable the possibility to develop complex relations between the shape of the workspace, links and geometrical dimensions in order to optimize the parallel structure.

The parallel structure parameterization enables the development of the geometric optimization and the robot workspace shape. The obtained results are useful for the designers in understanding the workspaces characteristics distribution and parallel robots optimization.

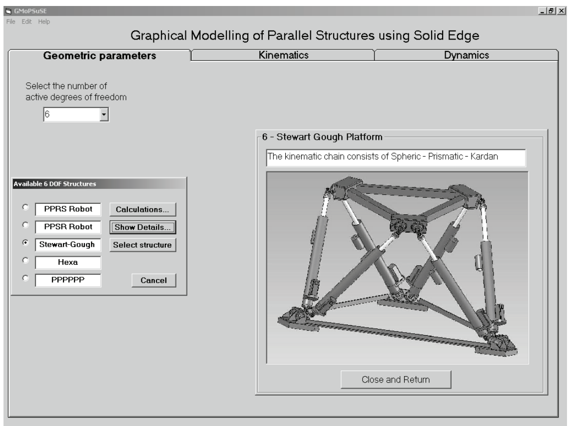

Figure 3: Simulation program for a 6-DOF parallel structure.

The presented simulation system enables the motion visualization in a modular manner valid for virtually any structure of parallel robot, introducing the kinematic and dynamic models over the virtual robot. The introduction of extra conditions related to any component is possible with a relative small number of actions. By using the graphical interface presented in Figure 3, the facilities of the simulation software enable to develop a complex study about the robot kinematics and dynamics in order to optimize the parallel structure.

5 CONCLUSIONS

In this paper a solution for solving of the inverse dynamics for a 6-DOF parallel robot conceived for a helicopter simulator has been presented. The dynamic model derived through virtual work principle has a compact form and offer the possibility of a more complex dynamic study in order to evaluate their dynamic capabilities and to generate innovative control algorithms.

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