23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

KINEMATIC INDEX PERFORMANCE OF TWO 6-RUS PARALLEL ROBOTS USED AS FLIGHT SIMULATOR

Clodoaldo Schutel Furtado Neto
Ciências Tecnológicas - Universidade do Estado de Santa Catarina, Rua Paulo Malschitzki 200, 89219-710, Joinville, Brasil
clo_ neto@msn.com

Anibal Alexandre Campos Bonilla
Centro de Educação Superior da Foz do Itajaí - Universidade do Estado de Santa Catarina, Avenida Central 413, 88330-668, Balneário Camboriú, Brasil
alexandre.campos@udesc.br

Alexandre Reis
Centro de Artes - Universidade do Estado de Santa Catarina, Avenida Madre Benvenuta 2007, 88035-001, Florianópolis, Brasil
a.a.reis@terra.com.br

Rodrigo Trentini
Rüdiger Kutzner
Faculty I - Electrical Engineering and Information Technology - University of Applied Sciences and Arts Hannover, Ricklinger Stadtweg 120, 30459, Hannover, Germany
rodrigo.trentini@hs-hannover.de
ruediger.kutzner@hs-hannover.de

Abstract. *Flight simulators are devices that help the flight crew training. Simulator main objective is is reduce operational costs, human and machine risks and recycling pilots under normal and adverse conditions, e.g. training at critical condition. The University of the State of Santa Catarina built a flight simulator based on 6-DoF axisymmetric parallel robot which incorporates virtual reality immersion environment. This flight simulator presents 6-RUS kinematic chain which is the second most common architecture for this application. Hunt proposed this chain architecture early in 1983. Parallel robots are closed-loop mechanisms that present good performance in terms of accuracy, rigidity and ability to manipulate large loads. This work aims to evaluate and compare the kinematic performance of 6- RUS parallel configuration robots using an algorithm based on parallel robot kinematics and then it is analyzed through a Computer Aided Engineering CAE software the obtained results and possible direct or inverse singularities closeness.*

Keywords: *Parallel Robot, Flight Simulator, 6-RUS, Direct singularity, Inverse singularity*

1. INTRODUCTION

The parallel robot studied in this work is a flight simulator built in UDESC - Ceart (Centro de Artes) in Florianópolis . This robot presents the second most common architecture for parallel robots used in flight simulator: the 6 - RUS. This work aims to evaluate and compare the kinematic performance of 6- RUS parallel configuration robots using an algorithm based on parallel robot kinematics. To evaluate this system it is used a work-based index. This index measures the robot closeness to the direct singularities.

This work aims to evaluate and compare the kinematic performance of 6- RUS parallel configuration robots using an algorithm based on parallel robot kinematics and then it is analyzed through a Computer Aided Engineering CAE software the obtained results and possible direct or inverse singularities closeness.

2. ROBOT ARCHITECTURES

As early as 1983 Hunt suggested a robotic architecture using this type of chain Hunt (1983). This parallel robot is composed of two platforms, one of them fixed to the ground,(base). On the base there are six rotating actuators R located on the edges of the triangle. These actuators are the input elements on which the active joints are located. Each actuator is linked to the end-effector through a rod. In each rod, one tip is linked to the crank of an actuator through an universal joint U and the other tip is connected to the end-effector by means of a spherical joint S. A couple of rods converge on each spherical joint of the end-effector (Zabalza *et al.*, 2003).

The HEXA parallel robot, first presented in (Pierrot, 1990) is a six degree of freedom DOF manipulator composed of six equally designed kinematic chains, which connect a base-platform to the end-effector platform. Each chain can be described as a serial RUS chain, where *R* stands for revolute joint, *U* for universal or cardan joint and *S* for spherical joint respectively, see Figure 5.

Figure 1. IWF-robot,Last *et al.* (2005).

The revolute joints of the HEXA's structure are the active joints, which means that they are driven by an actuator while spherical joints in the structure remain passive. A prototype of the HEXA parallel robot has been designed and built at the Institute of Machine Tools and Production Technology (IWF) in Braunschweig, Germany, from now on named IWF-robot, see Figure 1, (Last *et al.*, 2005).

Figure 2. CEART-robot,Last *et al.* (2005).

The flight simulator built at UDESC - Ceart (Centro de Artes) in Florianópolis also has a 6-*R*US parallel robots configuration. See Figure 2. Both configurations belong to the same family, so they have the same kinematic structure (Furtado *et al.*, 2014).

3. 6-*R*US INVERSE KINEMATIC

For inverse kinematic problem the vector describing moving platform position in cartesian coordinates system and orientation by roll, pitch and yaw angles respectively is given by $P = [P_x \;\; P_y \;\; P_z \;\; \varphi \;\; \vartheta \;\; \psi]$.

Few geometrical parameters are necessary to develop the inverse kinematic problem solution for 6-RUS parallel robot. Them can be obtained from the built prototype or the CAD model.

Required parameters are the fixed base radius r_b, moving platform radius r_p , half-distance between actuated joint pair d, half-distance between joints in moving platform e , crank dimension r_i which is located in active joint, rod dimension Rp , position angle of actuators pair χ_a, position angle of passive spherical joint in moving platform χ_j and the angle between the crank rotational plane and an axis parallel to y β (Campos *et al.*, 2013). These parameters are detailed in Figure 3.

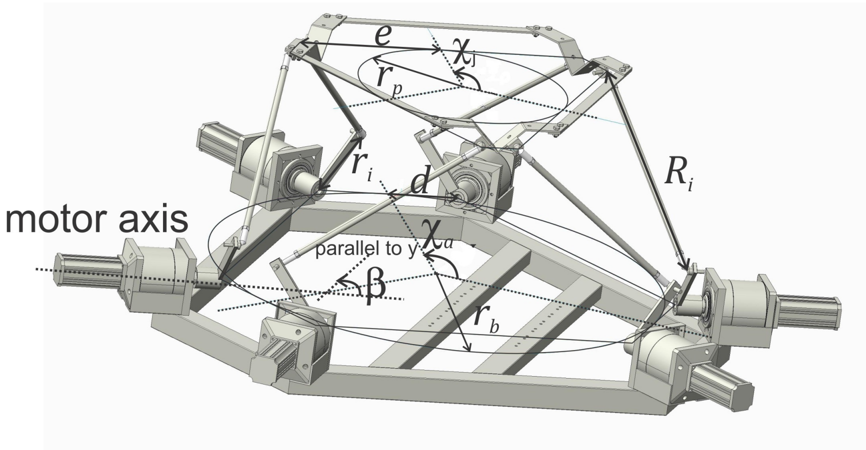

Figure 3. Parallel robot geometrical parameters (Campos *et al.*, 2013).

4. INVERSE SINGULARITY INDEX

The inverse singularity is caused due the serial nature of the legs and will occur in 6-*R*US parallel robots if one or more of the six legs are fully extended or fully contracted. This means the parallel robot loses one or more degrees of freedom, preventing some moves.

A way to check the proximity of the inverse singularity is to analyze the alignment between the crank and the passive link of each leg. This can be done from the kinematic equations. When inverse singularity occurs the root of the equation 1 is negative (q is an imaginary number),which means this leg can not be more extended or contracted because of crank and the passive link lengths.See Equation 1.

$$q = \sqrt{u^2 + v^2 - w^2} = \sqrt{-\mu} \quad (1)$$

So the singularity proximity can be evaluated by checking how close this root is next to become negative. For this does not occur the sum of geometric terms u^2 and v^2 must be greater than w^2. Thus a proximity index inverse singularity Inv_I of each leg may be defined as:

$$Inv_I = \frac{u^2 + v^2}{w^2}, Inv_I > 1 \quad (2)$$

5. DIRECT SINGULARITY INDEX

This index is develop using the screw theory, specifically the power or rate of work, to determine how close the parallel manipulator is to a direct singularity ((Lenar *et al.*, 1998); (Pottmann *et al.*, 1999). The power inspired measure determines closeness to singularity through an optimization problem that results in a corresponding generalized eigenvalue problem (Wolf and Shoham, 2003).

Been L_i the Plucker line coordinates and x the resulting twist.

In the case of parallel manipulators this is interpreted as the minimization of the instantaneous work generated by a set of wrenches, given by L_i , acting on a body instantaneously moving in a twist direction given by x. If a wrench is acting on a rigid body such that it produces no work while the body is undergoing an infinitesimal twist, the two are assumed to be reciprocal to each other and their reciprocal product is zero. This is the case in a singular configuration of the robot. Consider the Gough-Stewart platform shown in figure 4. The rows of the Jacobian matrix of the manipulator are composed of the Plucker coordinates of the wrenches acting along its limbs L_i. Applying the method to this set of wrenches while the platform is moving instantaneously along the twist direction given by x, the smallest L_i determines the direction along which the work generated by the set of wrenches is minimal. When the reciprocal product is zero, there is no work generated by the set of wrenches when the platform moves in the twist direction given by x. We use this physical interpretation of the reciprocal product of screws in order to investigate the behavior of a given robotics structure in a given configuration (Wolf and Shoham, 2003).

Theoretically the index value is supposed to be zero, but due joints clearance the value of the index to be a singularity is slightly higher (Last *et al.*, 2005). The singular range bound is experimentally identified as 0.029 W (IWF-Hexa Robot) and upon it the manipulator stiffness is warranted into the whole workspace (Hesselbach *et al.*). The index minimum value is determined by evaluating the built robot prototype belonging IWF-robot, this work suppose that CEART-robot have a similar value.

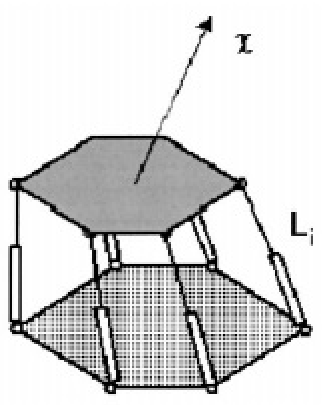

Figure 4. Gough-Stewart platform, the lines L_i and the resulting twists (Wolf and Shoham, 2003).

6. KINEMATICAL PERFORMANCE INDEX FOR TWO 6-RUS PARALLEL ROBOTS

The Six DOF IWF-robot is composed by six limbs connecting the basis to the end-effector, see Figure 5. Each limb contains an active rotative joint A_i (for $i = 1, \cdots, 6$) fixed to the basis, a passive universal joint B_i (composed by two orthogonal rotative joints) and a passive spherical joint C_i connected to the end-effector. The cranks and the passive links are connected at B_i.

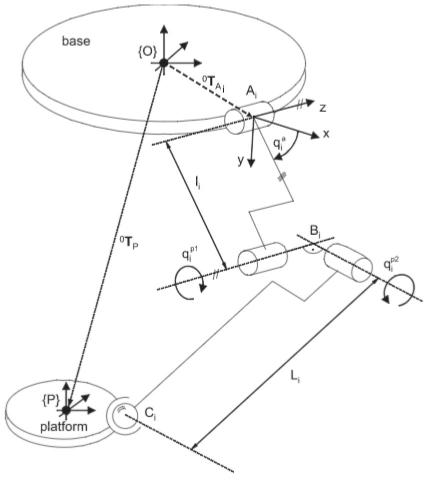

Figure 5. 6-Rus Kinematic Chain, (Last *et al.*, 2005).

As the IWF-robot and the CEART-robot robots that have same kinematic chain and therefore belong to 6-*R*US parallel manipulator family, it is possible to compare their performance in the same task and study the geometric differences and their influence on performance. The Ceart CEART-robot was conceived to result in a complete operating flight simulator built by the university UDESC (Universidade do Estado De Santa Catarina. Hence both configurations should be tested with a typical flight simulation task.

6-RUS parallel architecture may be considered as a parallel robots family. Each member of this family has different values for β_i angles. CEART-robot is a member of this family with $\beta_1 = 120$, $\beta_2 = 180$, $\beta_3 = 240$, $\beta_4 = 300$, $\beta_5 = 0$ and $\beta_6 = 60$, and IWF-robot is another member with $\beta_1 = 0$, $\beta_2 = 120$, $\beta_3 = 120$, $\beta_4 = 240$, $\beta_5 = 240$ and $\beta_6 = 0$.

6.1 IWF-robot and CEART-robot Performance for Flight simulator Task

The IWF-robot and CEART-robot may have just a few kinematic parameter values as difference, but they also have distinction of performance. From this,a question arises, what setting has the best performance for a flight simulation task?

The movement executed by the manipulator is a orientation rotation in the initial position. As the orientation rotations in Z axis can be easily performed by a additional motor, the optimization should be applied in orientations in XY plane. For a given χ_a and β_i angles (optimization parameter), a rotation is performed around all orientation axes in the plane

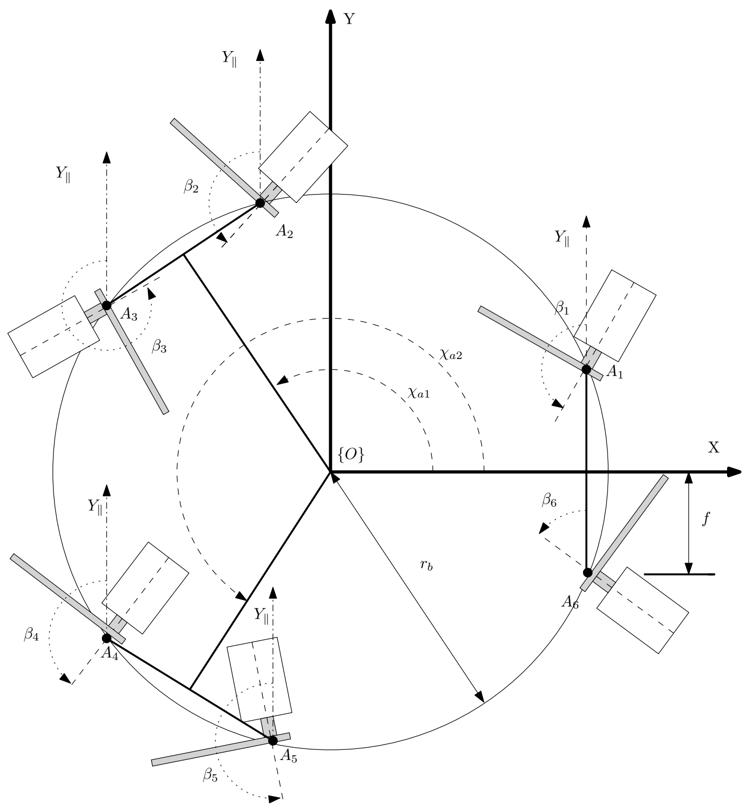

Figure 6. Base layout, where design parameters are χ_{a1} ,χ_{a2}, β_1, β_2, β_3, β_4, β_5 and β_6.

XY to verify where the rotation is minimum and its value.

6.2 IWF-robot and CEART-robot PERFORMANCE

In order to illustrate IWF-robot and CEART-robot maximum rotation around 360^o axes in XY plane, a polar graphics is made for each configuration. The inner circle represents the maximum rotation that the manipulator may perform in all orientation axes in the XY plane from 0^o to 360^o.

As figures 7 and 8 show, CEART-robot have a better performance than IWF-robot in this movement. If we have a closer look in these configurations it is possible to find deficiencies of each configuration. Therefore, using a kinematic algorithm, a new task consisting of performing rotations around one single axis in order to evaluate the kinematic index performance, can be done.

For instance IWF-robot with respect to Y axis,is shown in Figure 9. It is observed that it fails the minimum work index value in 18° of rotation in this axis. Which is the same angle present in Polar Graphic. Hexa configuration typicality have direct singularity issues.

The CEART-robot performance with respect to rotation around the Y axis, it didn't fail in the work index until more than 30° of rotation in this axis. However the polar graphic has a smaller rotation value, therefore it fails in the inverse singularity, see Figure 10. CEART-robot had a limited movement because the inverse singularity, shows up for 25° in this case, as Section 4 defined the inverse singularity problem.

6.3 Software Tool: ADAMS

This section presents CAE (Computed Aided Engineering) model analyses for IWF-robot and CEART-robot to confirm the developed algorithm results. Using the optimized parameters a CAE model for ADAMS is built to analyse 6-RUS optimized configuration. This parametric model is developed to enable the robot configuration update from a script. This script accesses another *.cmd* file containing the positions of the points A_i, B_i, C_i and the orientation of active joints to define 6-RUS in a new configuration. Then the optimized 6-RUS model is analysed to verify the direct singularity and inverse singularity proximity.

ADAMS (acronym of Automated Dynamic Analysis of Mechanical Systems) is a multibody dynamics simulation software equipped with Fortran and C++ numerical solvers. ADAMS was originally developed by Mechanical Dynamics Incorporation which then was acquired by MSC Software Corporation.

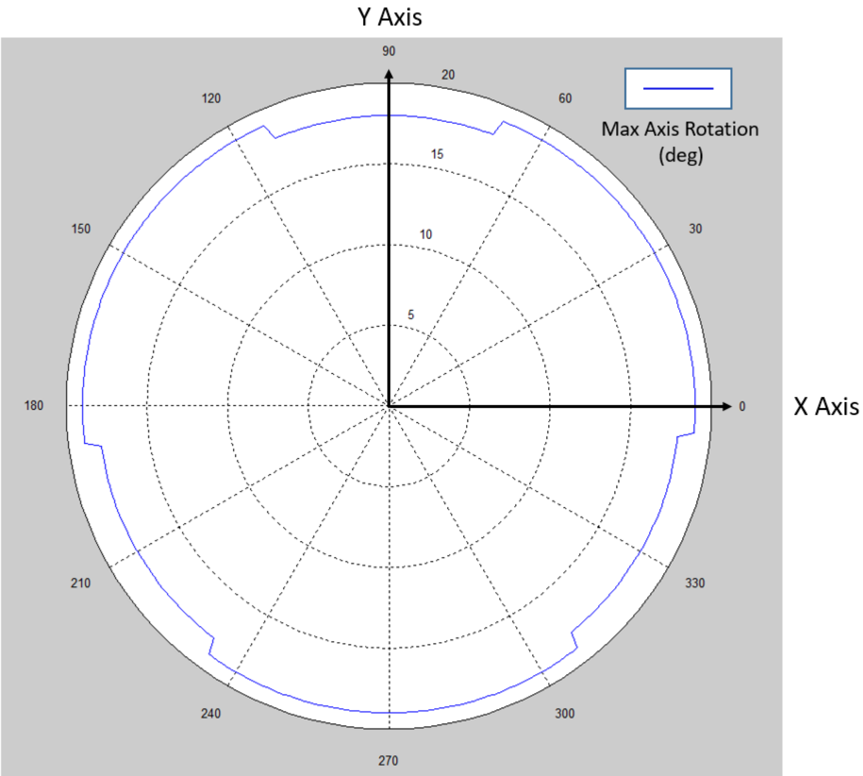

Figure 7. HEXA Polar Graphic.

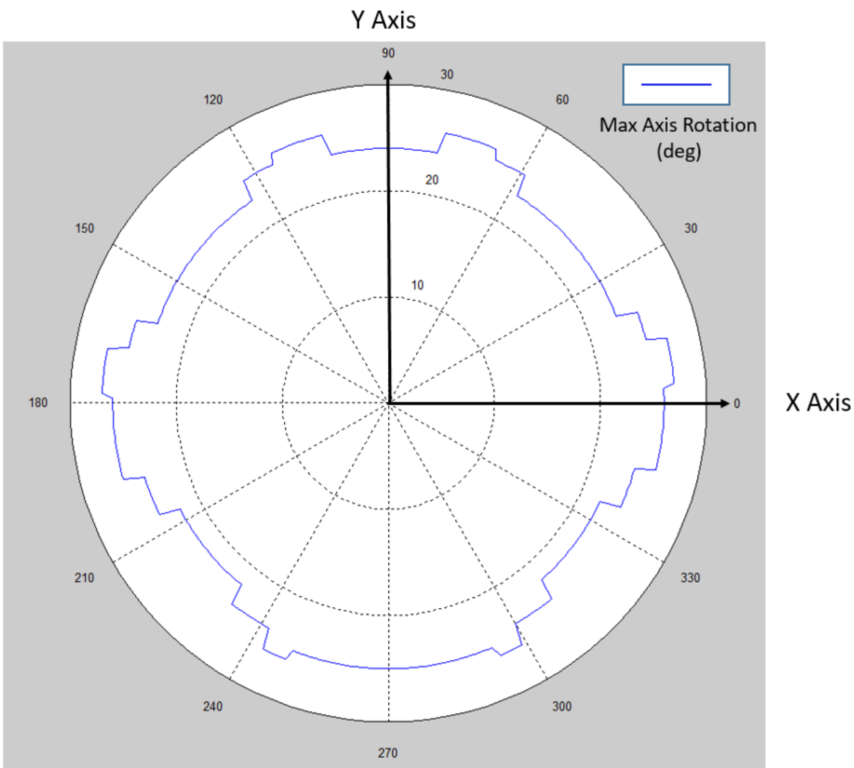

Figure 8. 6-*R*US Ceart's Polar Graphic.

6.3.1 CAE Analyze: HEXA Robot

Direct singularity problems mean that even with totally fixed limbs, there is an end-effector motion that may not be prevented. Therefore, in direct singular position, if forces/torques are applied to mobile end-effector, high magnitude

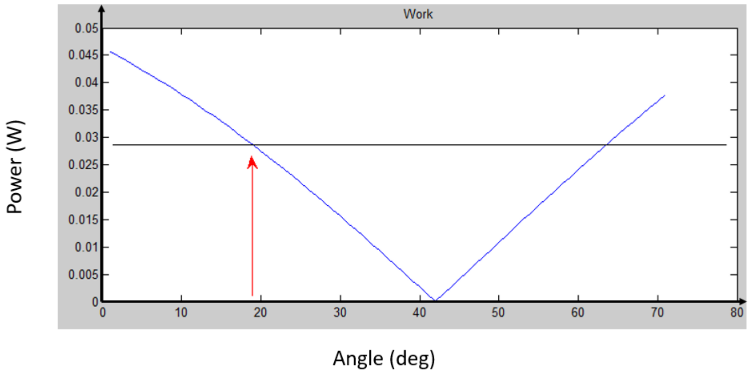

Figure 9. 6-*R*US Hexa Work, see red arrow.

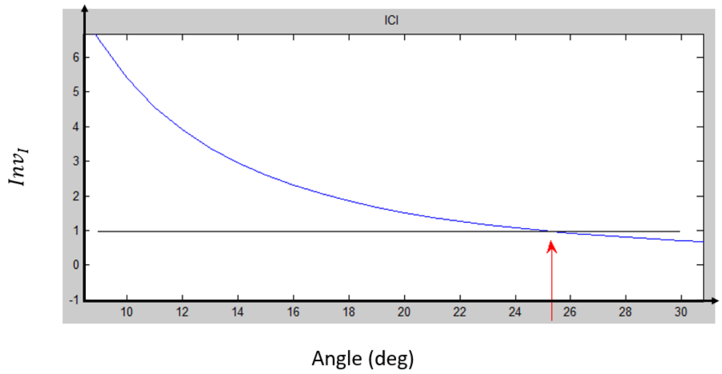

Figure 10. 6-*R*US Ceart's inverse constrain, see red arrow.

reaction force/torques may be appear in robot actuators.

Constant torques in all axis are applied in IWF-robot end-effector in original position. The magnitude of the reaction forces is smaller them 100 Newtons. The same constant torques are applied in IWF-Robot end-effector into a singular position. As expected the reaction forces are significantly greater in magnitude, up to approximately 4000 Newtons, see Figure 11.

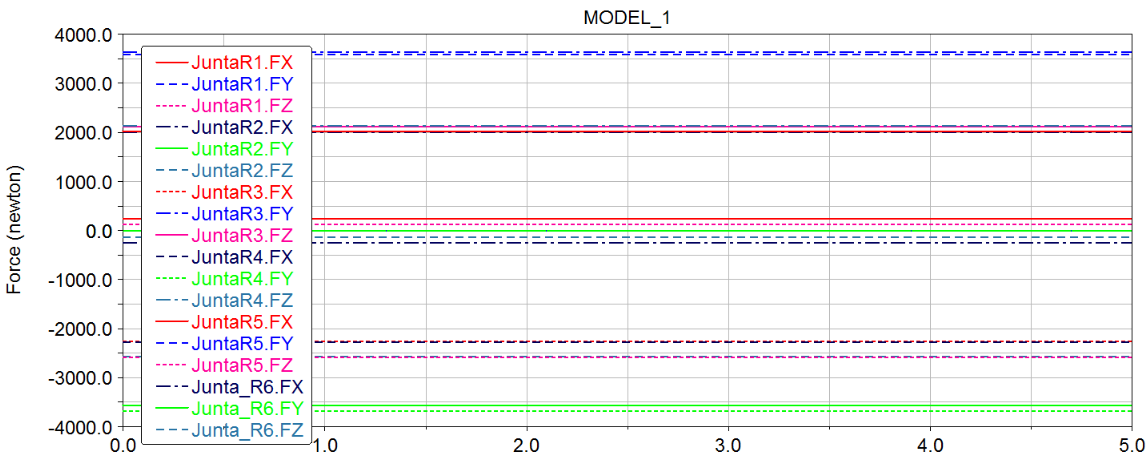

Figure 11. HEXA robot torque application near direct singularity.

6.3.2 CAE Analyze: CEART-robot

CEART-robot have inverse singularity issues as Matlab demonstrates, see Section 6.2. Inverse singularity may be detected by ADAMS executing a movement until singular position. The CAE models movement should be the same as performed by program.

Figure 12 shows that Cranks 3 and 4 have discontinuities in their movements at similar rotation angle 25°. Which means the legs are fully extended and ADAMS may automatic detect the inverse singularity when if some CAE model joint broken.

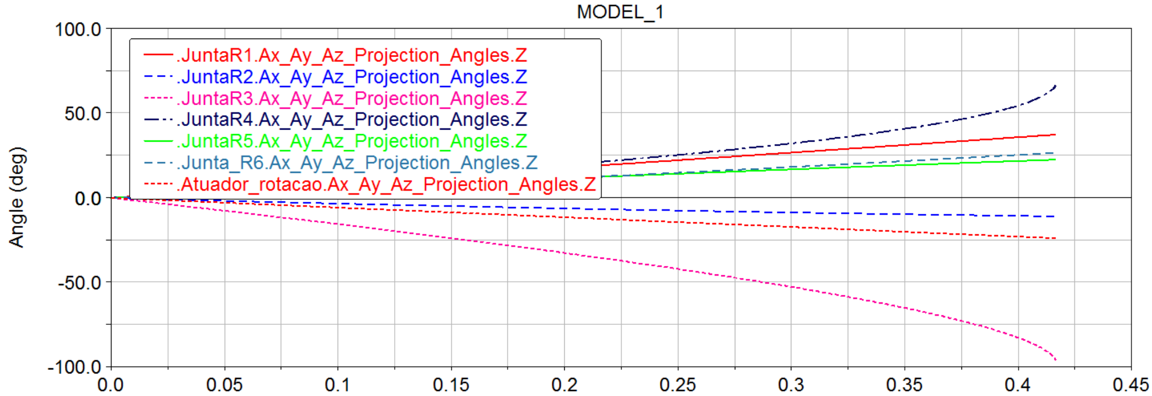

Figure 12. Ceart's rotation in Y axis, inverse singularity near 25°.

7. CONCLUSIONS

As figures shows, 6-RUS of Ceart have a better performance than 6-RUS-Hexa in this movement. It is shown that IWF-robot also belongs to the same family of CEART-robot, but it has distinct performances, which motivate the optimization of 6-RUS configuration in order to work as flight simulation. The proposed task is maximize the rotation of the end-effector around all axes in XY plane. Some important points are the apparent relationship among forward kinematics index and the inverse kinematics constrain with mobile end-effector size, this relationship may be observed in three points. That HEXA robot with little end-effector (compared with basis) have problem with direct singularity. In Ceart robot bigger mobile end-effector presents problems due inverse singularity.

8. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of Program: 3100 - Assistive Technology Support Program of CAPES, in Project: Reconfigurable Platform for Assistive Technology for Bedridden Patients within the Notice: Assistive Technology No. 59/2014.

9. REFERENCES

Campos, A., Faveri, G., Furtado, C., Reis, A. and Garcia, A., 2013. "Inverse kinematics for general 6-rus parallel robots applied on udesc-ceart flight simulator".

Furtado, C., Campos, A. and Reis, A., 2014. "Orientation workspace optimization for a 6-rus parallel robot".

Hesselbach, J., Campos, A., Bier, C. and Löwe, H., ???? "Direct kinematic singularity detection of a hexa parallel robot". Submited to ICRA2005, IEEE.

Hunt, K.H., 1983. "Structural kinematics of in-parallel-actuated robot-arms". *Trans. ASME, Journal of Mechanisms, Transmissions and Automation in Design*, Vol. 105, pp. 705–712.

Last, P., Budde, C., Bier, C. and Hesselbach, J., 2005. "Hexa-parallel-structure calibration by means of angular passive joint sensors". In *Mechatronics and Automation, 2005 IEEE International Conference*. IEEE, Vol. 3, pp. 1300–1305.

Lenar, J., Husty, M.L. *et al.*, 1998. *Advances in Robot Kinematics: Analysis and Control*. Springer.

Pierrot, F., 1990. "A new design of a 6-dof parallel robot". *J. of Robotics and Mechatronics*, Vol. 2, No. 4, pp. 308–315.

Pottmann, H., Peternell, M. and Ravani, B., 1999. "An introduction to line geometry with applications". *Computer-aided design*, Vol. 31, No. 1, pp. 3–16.

Wolf, A. and Shoham, M., 2003. "Investigation of parallel manipulators using linear complex approximation". *Journal of Mechanical Design*, Vol. 125, No. 3, pp. 564–572.

Zabalza, I., Pintor, J.M., Gil, J.J., Ros, J. and Jiménez, J.M., 2003. "Total and partial stationary configurations for a 6-rus hunt-type parallel manipulator". In *Proceedings of the 11th world congress in mechanism and machine science, IFTOMM*. pp. 18–21.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.