Study on Trajectory Planning for Space Simulator Based on Minimum Acceleration Limitation

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Abstract. Trajectory planning and simulation of docking tests on the ground for space simulator is one of key technologies to complete space docking mission. A new time-optimal trajectory planning algorithm is proposed based on minimum acceleration limitation. It is realized by searching maximum acceleration to obtain the best time according to PSO (particle swarm optimization). Through calling matlab script by LabView and capturing control set points, 3D CAD model is driven to verify the rationality of the trajectory planning algorithm and model design. The simulation results show that the simulator using the proposed algorithm can move smoothly and reliably meeting the experiment requirements.

Introduction

Space simulator must meet some constraints such as moving along specified trajectory or meeting displacement, speed and acceleration constraints when executing docking mission, so it is necessary to plan space simulator’s trajectory.

Through taking position error square minimum and acceleration square minimum as weighted index function, a new optimal quintic polynomial trajectory planning method for industrial robot is proposed by Yucheng Li, which can avoid robot reciprocating motion caused by the characteristic of quintic polynomial [1], but it needs a large amount of calculations. In order to overcome above shortcomings, a new time-optimal trajectory planning method based on minimum acceleration limitation is proposed. Through searching maximal acceleration based on PSO to achieve the best time, the algorithm ensures that space simulator cannot move repeatedly, reduce the amount of calculations and provide theoretical guidance for practical engineering applications.

Virtual prototype motion simulation based on NI LabView and Solidworks can realize visualization of the movement process, verify rationality of trajectory planning algorithm and achieve collision detection. The basic theory of joint motion simulation between NI LabView and Solidworks is introduced by Huineng Wang who realizes the fixed-point displacement and velocity track detection [2]. Continuous trajectory detection is realized which can provide reference to trajectory planning algorithm. The visualization of movement process can be convenient for development team to communicate, improve the development efficiency and shorten the development cycle.

Docking Principle

Space simulator is comprised of active side and passive side. In the process of realizing docking, passive space simulator which is static relatively in orbit adjusts the docking attitude rightly. Active space simulator runes to docking position along set trajectory and satisfies initial docking requirements at the docking time. In the task, the success of docking is the basis of subsequent tasks [3].

It is necessary to study on trajectory planning for space simulator because meeting docking initial conditions at the specified position is precondition for the success of docking. The general method for trajectory planning is that set path is interpolated or approximated by polynomial
functions to produce a series of “set control points” to control space simulator [4]. The general method has cubic polynomial interpolation and cubic polynomial interpolation across the path point and so on. Firstly, traditional quintic polynomial interpolation is introduced; secondly, a new time-optimal trajectory planning algorithm based on minimum acceleration limitation is proposed; lastly, joint motion simulation between NI LabView and Solidworks is used to verify the rationality of algorithm and reliability of space simulator assembly.

Algorithm Design

12-DOF space simulator’s path, velocity and acceleration curve should be continuous on condition that it meets the movement initiation and termination conditions in order to move smoothly, reduce vibration and damage for mechanism. 6-DOF position movement doesn’t need to consider the impact of acceleration, the higher degrees of polynomial interpolation, the higher interpolation precision. Quintic polynomial interpolation is accepted under the condition that 6-DOF position movement meets docking preconditions. However, 6-DOF posture movement needs to consider the impact of acceleration, a new time-optimal trajectory planning algorithm is proposed based on minimum acceleration limitation under the condition that 6-DOF posture movement meets docking preconditions.

Trajectory Planning Without Minimum Acceleration Limitation. Trajectory planning in 12-DOF task space can be divided into trajectory planning in 1-DOF. As much as possible to ensure acceleration curve continuous and satisfy displacement, velocity and acceleration constraints in order to make space simulator move placidly and movement curve smooth. The higher degrees of traditional polynomial interpolation, the more constraints it can satisfy [2]. Quintic polynomial interpolation algorithm is adopted to plan displacement trajectory.

Interpolation function:

\[
Y_j(t) = a_j t^5 + b_j t^4 + c_j t^3 + d_j t^2 + e_j t + f_j, \quad j = 1, 2, 3
\]

(1)

Coefficients can be attained from (2), and then the trajectory curve can be reached. A series of “set control points” can be reached with a certain sampling time interval.

Trajectory Planning With Minimum Acceleration Limitation. In practical engineering, 6-DOF posture movement should meet the minimum acceleration limitation, and ensure that the execution time is optimal. So it is necessary to mend current trajectory planning algorithm on conditions that movement curve is smooth and satisfies the minimum acceleration limitation, posture and velocity’s initial values. A new time-optimal trajectory planning algorithm based on minimum acceleration limitation is proposed.

Principle: Suppose minimum acceleration \(a_{\text{min}}\), maximum acceleration \(a_{\text{max}}\) which can be searched based on PSO. In the period \(t \in [t_0, t_1]\), space simulator does accelerated motion that acceleration ranges from \(a_{\text{min}}\) to \(a_{\text{max}}\); in the period \(t \in (t_1, t_2]\), it does uniform motion; in the period \(t \in (t_2, t_k]\), it does decelerated motion that acceleration ranges from \(-a_{\text{min}}\) to \(-a_{\text{max}}\). In each period, trajectory planning method is on the basis of quintic polynomial interpolation. The period of uniform motion can adjust in order to satisfy preconditions of docking. Optimal execution time can be attained through program searching based on PSO.
\[
\begin{bmatrix}
t_3^3 & t_2^2 & t_1 & 1 \\
3t_3^3 & 2t_2 & 1 & 0 \\
6t_1 & 2 & 0 & 0 \\
6t_1 & 2 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
a_j \\
b_j \\
c_j \\
d_j \\
\end{bmatrix}
= 
\begin{bmatrix}
Y_j(t_0) \\
\dot{Y}_j(t_0) \\
\ddot{Y}_j(t_0) \\
3 \\
\end{bmatrix}
\] (3)

\[
\begin{bmatrix}
\dot{Y}_j(t) = Y_j(t_1) + \dot{Y}_j(t_1)(t-t_1) \\
\ddot{Y}_j(t) = \ddot{Y}_j(t_1) \\
\dddot{Y}_j(t) = 0 \\
\end{bmatrix}
\] (4)

\[
\begin{bmatrix}
t_2^3 & t_2^2 & t_2 & t_2 & 1 \\
5t_2^3 & 4t_2^2 & 3t_2 & 2t_2 & 1 & 0 \\
20t_2 & 12t_2 & 6t_2 & 2 & 0 & 0 \\
T_k & T_k & T_k & T_k & T_k & 0 \\
5T_k & 4T_k & 3T_k & 2T_k & 1 & 0 \\
20T_k & 12T_k & 6T_k & 2 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
a_j \\
b_j \\
c_j \\
d_j \\
d_j \\
e_j \\
f_j \\
\end{bmatrix}
= 
\begin{bmatrix}
Y_j(t_2) \\
\dot{Y}_j(t_2) \\
\ddot{Y}_j(t_2) \\
\dddot{Y}_j(T_k) \\
\dddot{Y}_j(T_k) \\
\dddot{Y}_j(T_k) \\
\dddot{Y}_j(T_k) \\
\end{bmatrix}
\] (5)

Coefficients can be attained from (3)(4)(5), and then the trajectory curve can be reached. A series of “set control points” can be reached with a certain sampling time interval.

**Virtual prototyping motion simulation**

Motion analysis of assembly can be done by animator in Solidworks, which can drive assembly through “set control points” and attain displacement, velocity and acceleration curve. However, the disadvantages are that users cannot control the process of assembly movement and display some relative parameters in real time. In order to overcome above disadvantages, joint motion simulation between NI LabView and Solidworks is proposed.

**Motion Simulation Principle.** User control interface is developed in NI LabView, trajectory planning algorithm can be realized by NI LabView calling matlab script, capturing motion control set point to save them at a certain time interval. The assembly of space simulator has finished fitting together relatively in Solidworks. Motion control program and assembly of space simulator must be added in the same project. Virtual motion axis which is corresponding to virtual motor in Solidworks can be built by NI softmotion mapping and selecting and added into LabView project automatically. Motion simulation can be achieved through the motion control program controlling the virtual axis which is input of NI softmotion function.

NI softmotion communicates with Solidworks assembly through Scan Engine. Scan Engine captures data at a certain communication cycle to display in user control interface, and send data to drive model in real time.

![Fig.1 Interactive schematic between NI LabView and Solidworks](image)

The sampling time of algorithm is usual 10-20ms. However, drive cycle of servo controller is general microseconds. In order to make movement error approximate zero, the contiguous two “control set points” must be interpolated. NI softmotion simulates this time difference fully, the trajectory between contiguous two “control set points” can be configured in Axis Property.
There are two methods in Spline Configuration, which are Cubic B Spline and Catmull-Rom Spline. The main difference between them is whether they pass all interpolation points or not. B Spline doesn’t need to pass all interpolation points, while Catmull-Rom Spline needs to pass.

The sequence of 12-DOF movement which is also called movement timing logic design can be realized by the execution sequence of NI softmotion function. The basic form of assembly movement can be divided into serial sequence and parallel sequence. There are two ways to realize and control the sequence of virtual axis, one is that NI softmotion function ports which are ‘execute’ (rising edge triggered) and ‘done’ can be triggered by inner logic, the other is that NI softmotion function ports can be triggered by out signals [2].

LabView is a kind of graphical programming language based on data flow with multi-threaded parallel execution characteristic, so it is convenient to realize certain DOF movement for space simulator at the same time.

**User Interface Design.** The following function is realized by the motion simulation program. Firstly, input some parameters, such as displacement, velocity, acceleration, posture and other parameters and select trajectory method to reach ideal trajectory curve. Secondly, capture motion control points at a certain time interval and display them in user interface in real time. Thirdly, the movement sequence of 12-DOF which reaches through parameter identification can display in user interface in real time. Lastly, planning trajectory curve and real motion curve can display by XY graph in user interface in real time, which helps analyzing motion error and plays an important impact on control algorithms design of servo controller.

**Simulation Results**

1-DOF initial conditions conclude displacement, velocity and acceleration, whose numerical value is all 0; terminal conditions conclude displacement, velocity and acceleration, whose numerical value is 3m, 0.3 m/s, 0 separately. The simulation figure is shown in Fig.5.
1-DOF initial conditions conclude displacement, velocity and acceleration, whose numerical value is all 0; terminal conditions conclude displacement and velocity, whose numerical value is 0.175rad, 0.0175 rad/s separately. In addition, initial conditions conclude minimum acceleration limitation, whose numerical value is 0.025 rad/s². The simulation figure is shown in Fig.6.

Fig.6 1-DOF trajectory planning with minimum acceleration limitation

3-DOF initial conditions conclude displacement, velocity and acceleration, whose numerical value is all 0; terminal conditions conclude displacement and velocity, whose numerical value is (3m, 1.5m, 2m), (0.3m/s, 0.15m/s, 0.15m/s) separately. In addition, initial conditions conclude minimum acceleration limitation, whose numerical value is (0.025 m/s², 0.01 m/s², 0.01 m/s²). The simulation figure is shown in Fig.7.

Fig.7 3-DOF trajectory planning with minimum acceleration limitation

1-DOF initial conditions conclude displacement, velocity and acceleration, whose numerical value is all 0; terminal conditions conclude displacement and velocity, whose numerical value is 3m, 0.3 m/s separately. In addition, initial conditions conclude minimum acceleration limitation, whose numerical value is 0.025 m/s². The real motion curve of model is shown in Fig.8.

Fig.8 1-DOF real trajectory with minimum acceleration limitation

**Conclusion**

According to the simulation results, a time-optimal trajectory planning algorithm proposed based on minimum acceleration limitation can ensure the continuity of trajectory, the consistency of acceleration and velocity in relative periods of time, and reduce the amount of computation. Virtual prototype motion simulation realizes the trajectory evaluation, collision detection, and the visualization of 3D model motion process which provides reference to find the problems of design and shorten the development cycle. This paper gives a certain reference value for other motion control simulation system and provides theoretical guidance for spacecraft docking in orbit.
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