



Research paper

Optimal design of SINS's Stewart platform bumper for restoration accuracy based on genetic algorithm

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ABSTRACT

The strap-down inertial navigation system (SINS) is a standard and crucial approach for attitude determination of a ship. To protect the SINS from vibration and shock, we design a Stewart platform based bumper considering the high restoration accuracy requirement of the bumper. However, reset errors of buffer bars and wear of spherical hinges will change structure parameters of the bumper and degrade the restoration accuracy. In this paper, we propose an optimal design methodology for SINS's Stewart platform bumper to improve the restoration accuracy. First, the equation of restoration accuracy was derived using total differential method. Then, based on the equation, objective function, design variables and constraints are designated, so the structural optimization problem was transferred to a numerical optimization question. Later, genetic algorithm (GA) was employed to solve the numerical optimization matter. Afterwards, comparison results among GA, sequence quadratic programming (SQP) method and interior point method indicate that the proposed method can provide optimized structural parameters of SINS's Stewart platform bumper for restoration accuracy, which is 31.81" at the lever of current mechanical manufacturing lever. Finally, a real shock experiment for optimal designed bumper validates the proposed method.

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1. Introduction

The integration of the global position system (GPS) and the strap-down inertial navigation system (SINS), which can provide a more accurate and reliable navigation performance than any stand-alone system, has become a standard approach for position, velocity and attitude determination of a moving vehicle [1,2]. Discriminatingly, position and velocity are relatively precisely to acquire adopting the GPS, and we depend most on the SINS to get the attitude [3]. As for ship borne high-accuracy SINS/GPS attitude determination system, standard deviations of heading errors are $\pm 2^\circ$ and $\pm 5^\circ$ in mooring and sea tests, respectively [4]. However, the ship borne SINS are subject to vibration and shock due to marine power plant, sea wave, explosion and other external vibration sources. Vibration and shock will degrade the performance of the SINS rapidly. In order to circumvent the problem, a bumper for the SINS must be inserted in the vibration transmission path between SINS and hull deck.

Vibration isolation system using rubber absorbers have been widely employed as the optimal method for SINS [5]. However, the bumper for SINS is expected to attenuate vibration while the restoration accuracy requirement is stringent because of the high attitude accuracy of SINS. Rubber absorber cannot provide satisfactory restoration accuracy because of aging and

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Nomenclature

o	Center of mobile platform
O	Center of static platform
$o - xyz$	Mobile platform frame
$O - XYZ$	Static platform frame
A_i	Upper spherical hinges centers
$\mathbf{a}_i$	Coordinates of A_i in $O - XYZ$
B_i	Lower spherical hinges centers
$\mathbf{b}_i$	Coordinates of B_i in $O - XYZ$
$\mathbf{S}_i$	Vectors of buffer bars in $O - XYZ$
$\mathbf{s}_i$	Unit vectors of buffer bars in $O - XYZ$
$\mathbf{q}$	Generalized coordinate of the mobile platform
$\mathbf{p}$	Position vector of o in $O - XYZ$
Φ	Attitude vector of the mobile platform
$\alpha; \beta; \gamma$	Euler-angles of mobile platform
$\delta \mathbf{l}_i$	Reset errors of buffer bars
l_i	Lengths of buffer bars
δl_i	Length errors of buffer bars
$\delta \mathbf{e}$	Wear errors of spherical hinges
$\mathbf{R}$	Rotation matrix of platform
h	Height of the bumper
R_a	Radius of the mobile platform
R_b	Radius of the static platform
β_s	Half flare angle of adjoining spherical hinge on static platform
α_m	Half flare angle of adjoining spherical hinge on mobile platform

creep. More recently, several bumpers based on Stewart platform have been proposed to replace rubber absorbers to enhance the restoration accuracy of the bumper, such as a track-position and vibration control device of the Stewart platform for instruments in an on-orbit spacecraft [6], a six-axis electromagnetic relaxation isolator for precision payloads [7], an isolation system for a single gimbal control gyro [8], and other bumpers, because the Stewart platform possesses significant advantages in terms of dynamic properties, load-carrying capacity, high accuracy, and stiffness or stability [9]. So, we design a bumper based on Stewart platform for SINS to reduce the influence of vibration and shock on the performance of SINS and guarantee the restoration accuracy requirement.

The bumper based on Stewart platform for SINS connects the moving platform and the static platform with six buffer bars and each buffer bar has two spherical hinges, so the bumper has six degrees of freedom. The damping principle of bumper is bidirectional linear movements of buffer bars. The bidirectional linear movement of each buffer bar transforms the kinetic energy of vibration and shock to potential energy and finally to internal energy. However, reset errors of buffer bars and wear of spherical hinges, which change structure parameters of the bumper, result in the decrease of restoration accuracy. Meanwhile, mechanical design plays an important role in accuracy according to kinematic modeling and analysis [10–13].

In order to improve the restoration accuracy, optimization algorithms are applied to optimize structure parameters of the bumper. More recently, several techniques based on modern intelligent optimization methods have been proposed to optimize structure parameters of Stewart platform. Su et al. [14] present a real-coded genetic design methodology for an optimal kinematic Stewart platform to improve the kinematic accuracy of the fine tuning platform for a large radio telescope. Ahmad et al. [15] developed an optimization approach for the robust design of six degrees of freedom devices based on Monte Carlo simulation (MCS), while genetic algorithm (GA) and the approach are compromised enabling the designer to evaluate trade-offs between allowed performance variations and tolerances cost. Sergio et al. [16] used Motion Cueing Algorithms (MCA) for self-motion generation in VR simulators. Andrea Cirillo et al. [17] studied an approach based on GA to support the design of a cost-effective Stewart platform-based mechanism in order to maximize the payload and minimize the forces at each leg. Multi-objective optimization methods based on GA and Monte Carlo method for Stewart platform are widely used to improve the performance of parallel manipulator by taking account simultaneously several criteria [18–20].

As mentioned previously, most of optimization methods for Stewart platform mechanisms parameters based on modern intelligent optimization algorithms focus on moving kinematic performance of the platform regarding the parallel platform as a movement mechanism. However, we do not need to consider the movement features of the Stewart platform as a bumper for SINS while we attempt to optimize the static restoration accuracy, which are vulnerable to the reset errors of buffer bars and wear of spherical hinges. So the optimal methods for Stewart platform based mechanisms are not suitable for bumpers for SINS. Meanwhile, there are significant differences between bumpers presented by other scholars and bumper for SINS as bumper for SINS should afford shock and keep high restoration accuracy.

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