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Attitude pointing schemes and spacecraft configurations for libration-point-orbit spacecraft

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ABSTRACT

The libration points in the Sun–Earth or Earth–Moon systems have potential applications in observing solar activities (EL_1), space-based observatories and infrared astronomy (EL_2), half-way space-stations for lunar exploration (LL_1) and communications for satellites on Moon's far side (LL_2). Different from the traditional design methodology for libration point missions, new attitude pointing schemes are proposed in this paper to guide the design of spacecraft configurations based on the ideas of removing rotating components as much as possible. The fixed installations of transmission antenna, radiating surface and solar array make the SSO platforms of satellite be qualified for the EL_1- or EL_2-point mission with further advances in fixing the array and removing the battery. The fixed transmission antenna and zero-incident-angle array make the GEO platforms be qualified for the LL_1- or LL_2-point mission with improvements on killing the worst incident angle of $\pm 23°26'$ and the umbra/penumbra at vernal equinox. Addressed are the structure of attitude determine and control system, the analytic algorithm to derive the orbital frame and the performance of this control system.

1. Introduction

Gravitationally equilibrium points between the Sun and Earth (or the Earth and Moon) are called the libration points, where a spacecraft is able to maintain stationary with respect to the primary and secondary bodies without fuel consumption. Meanwhile, the EL_1 point in the Sun–Earth system has advantages of observing solar activities due to its special geometry, and a spacecraft around this point can warn of solar winds an hour before they reach the Earth so that the failure of communication signals are avoided, such as International Sun–Earth Explorer 3 (abbr., ISEE-3, launched in 1978) [19], Solar Heliospheric Observatory (abbr., SOHO, launched in 1995) [6], Interplanetary Physics Laboratory (also named 'Wind', launched in 1994) [11], Deep Space Climate Observatory (launched in 2015) [25], LISA Pathfinder (launched in 2015) [1]. The EL_2 point is a good location for space-based observatories and infrared astronomy due to the same relative position with respect to the Sun and Earth and the much-blocked solar radiation. Probes including Wilkinson Microwave Anisotropy Probe (launched in 2001) [13], Herschel and Planck Space Observatory (launched in 2009) [17], and Gaia (launched in 2013) [12] were allocated at EL_2 point for relevant missions.

Compared with applications exerting the Sun–Earth EL_1 and EL_2 points for the space-based observatories, deployments around the Earth–Moon LL_1 and LL_2 points can be used for lunar explorations: a half-way manned space station is expected to be placed at LL_1 point, aiming to transport cargoes and personnel to the Moon and back around, and the LL_2 point is considered as a perfect location for communication satellite covering the Moon's far side and for a propellant depot as part of the proposed depot-based space transportation architecture, including the Chang'E-2 and Chang'E-5T1 arriving at the LL_2 point on 2012 and 2014 respectively [14, 7], and the ARTEMIS mission [15], an extension of the THEMIS, arriving at LL_1 point on August 2010 [20]. Actually, the bounded trajectories around the libration points (referred to libration point orbit, abbr., LPO) are preferable for potential aerospace missions, because it requires less cost of inserting to LPOs than to libration points, and placing satellites on LPOs near EL_1 point can reduce sunshine disturbance on telecommunication signals.

So far, NASA, ESA and CNSA have sent 13 spacecraft to halo or quasi-halo orbits near libration points, and planned missions such as James Webb Space Telescope at EL_2 point [4], which is the most expensive space mission, and China's first EL_1 point mission Kuafu [21]. Generally speaking, the larger distance between the spacecraft and an Earth-based ground station is, the more complicated configurations the spacecraft must have. The configurations of most of the LPO spacecraft are complicated enough for active temperature controllers, except for one-dimensional solar array track-

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ing the sunlight and movable transmission antennas. However, the movable parts equipped on spacecraft cause the uncontrollable flexibility. Launched on August 12, 1978, ISEE-3/ICE weighs 478 kg and moves along a Halo orbit with a period of 178 days near SL_1 in the Sun–Earth system, serving for comet exploration during its 32-year life span. For S band communication and plasma research, ISEE-3 is instrumented with four 49-meter-long antennas, rotating at 20 rpm, and a pair of solar sensors, which provides attitude estimation at an accuracy of 0.1°. Twelve hydrazine thrusters are utilized for attitude and orbit control. Launched on December 12, 1995, SOHO weighs 1861 kg and moves on a Halo orbit with a period of 180 days near SL_1 in the Sun–Earth system, serving for Sun explorations. It is three-axis-stabilized and equipped with several instruments continuously pointing to the Sun, including a high- and low-gain antennas, of which the nominal attitude is set as x axis continuously pointing to the Sun and y axis to the north pole of ecliptic. ACE is launched on August 25, 1997, to monitor Solar winds and cosmic X-rays [9]. ACE weighs 785 kg and measures 1.6 m × 1.6 m × 1 m, moving on a Halo orbit near SL_1 in the Sun–Earth system. It is equipped with four solar arrays providing 500 W electric power as well as a magnetometer attached to them. ACE rotates at 5 rpm along the Sun–Earth direction and most of scientific instruments are assembled on the upper side of the solar arrays facing the Sun. Launched in June 2001, MAP weighs 840 kg and moves on a Halo orbit around SL_2 in the Sun–Earth system to measure the cosmic background radiation temperature [2]. Spinning at 0.464 rpm, it is non-active thermal controlled, thus the payloads must be kept from solar radiation. Its solar arrays are fixed and non-adjustable, so the incident angle of the Sun varies within a certain range. Launched on August 8, 2001, Genesis weighs 636 kg and moves on Halo orbits near EL_1 and EL_2 in the Sun–Earth system, serving for sample return of solar wind during its life span of 3 years [3]. The probe spins stably at 37.5 s/r and is instrumented with two fixed solar arrays, providing maximum energy of 254 W to nickel–hydrogen storage battery. The fixed antennas of S band work for communication between Genesis and the ground station on the Earth, and the temperature control is conducted through heaters and passive thermal controllers. Launched on May 14, 2009, Herschel and Planck move along Lissajous orbits near EL_2 in the Sun–Earth system, serving for far-infrared astro-observation and cosmic microwave radiation exploration. The scientific instruments inside Herschel need to work at zero degree, thus there is a fixed sky shade covering the upper instruments and a sunshading board covering those at bottom, where solar cells are assembled to provide electric energy for the probe. The circular solar arrays of Planck are fastened at the bottom of the probe so that they can keep pointing to the Sun as the probe spins by its vertical axis. The attitude control system is designed for quick orientation by star tracking locators as main attitude sensors.

From the viewpoint of spacecraft design, the spacecraft configuration depends on its attitude pointing scheme: for an Earth's satellite on a Sun-synchronous orbit (abbr., SSO), it is designed with one-dimensional solar arrays tracking the Sun and a fixed heat radiating surface at the right side of its hexahedral structure due to the nominal attitude pointing along the vehicle velocity, local horizontal (abbr., VVLH) coordinate frame; for a spacecraft on a geostationary orbit (abbr., GEO), it is designed with one-dimensional solar arrays perpendicular with the Equator due to the same attitude pointing scheme as well. Thus, a suitable attitude pointing scheme will contribute significantly to the configuration design. Aiming at both the LPO spacecraft in the Sun–Earth and Earth–Moon systems, two new attitude pointing schemes are defined in this paper with the corresponding designate configurations used for the temperature controller and solar power collector. An interesting conclusion is achieved that LPO in the Sun–Earth system has the similar design methodology in spacecraft configuration with SSO, and LPO in the Earth–Moon system is similar with GEO.

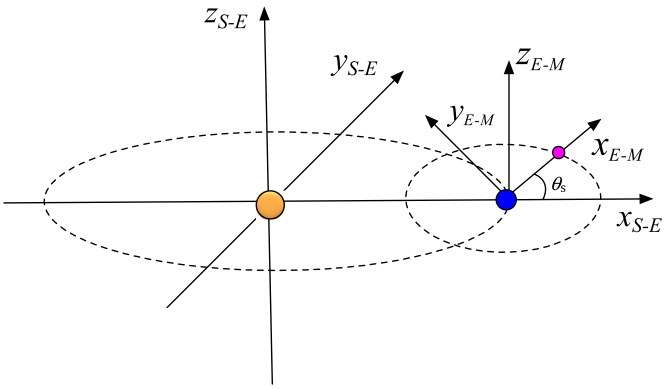

Fig. 1. The schematic of BCM: yellow, brown and plum dots indicate the Sun, Earth and Moon, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Nominal libration point orbits and mission analysis

Nominal libration point orbits in both the Sun–Earth and Earth–Moon systems are refined by an algorithm called multiple shooting corrector (abbr., MSC), which is very powerful to generate quasi-halo orbits in the restricted four body problem, e.g., the Sun–Earth–Moon–spacecraft system. In this paper, for simplicity, an analytic bi-circular model (abbr., BCM) of the restricted Sun–Earth–Moon system is used to generate nominal trajectories, although the MSC algorithm is available to deal with the ephemeris model.

In a BCM, the Earth and Moon are treated as independent gravitational points in their respective Keplerian circular motion about their barycenter with the eccentricity and inclination ignored, and the same treatment for the Sun and the Earth is employed. There exists two rotating frames in this model, one of which is to define the x_{S-E} axis from the Sun to Earth and the z_{S-E} axis perpendicular with the ecliptic plane, denoted by $\Re_{S-E}$, and the other of which is to define the x axis from the Earth to Moon and the z axis perpendicular with the lunar plane, denoted as $\Re_{E-M}$. Besides, there exists two unit normalizations in this model, one of which is to define the unit of length and mass as the distance between the Sun and Earth and the total mass of the two bodies, denoted by U_{S-E}, and the other is to define the unit of length and mass as the distance between the Earth and Moon and the total mass of the two bodies, denoted by U_{E-M}. Thus, the geometrical relationship between the three bodies can be presented by the angle between the two x axes, denoted as the Sun's angle θ_s. The schematic of BCM is shown in Fig. 1.

In order to generate natural orbits around the libration points, the MSC algorithm is applied in this paper, which is widely used in the computation of unstable periodic orbits with long periods [26], such as solar sail's displaced orbits [22] and J_2 invariant relative orbits [23]. For detailed description about MSC algorithm please refer to the work of Goméz et al. [8] and Xu et al. [24]. An initial iteration based on the natural solution of the dynamics is necessary to increase the convergence speed of the algorithm. The following Richardson expansion derived from the Lindstedt–Poincaré method [16,18] can perform as an effective initial value:

$$\begin{cases} x = a_{21}A_x^2 + a_{22}A_z^2 - A_x\cos\omega t + \left(a_{23}A_x^2 - a_{24}A_z^2\right)\cos 2\omega t \\ \quad + \left(a_{31}A_z^3 - a_{32}A_xA_z^2\right)\cos 3\omega t \\ y = \kappa A_x \sin\omega t + \left(b_{21}A_x^2 - b_{22}A_z^2\right)\sin 2\omega t \\ \quad + \left(b_{31}A_x^3 - b_{32}A_xA_z^2\right)\sin 3\omega t \\ z = \pm A_z\cos\omega t \pm d_{21}A_z[\cos 2\omega t - 3] \\ \quad \pm \left(d_{32}A_zA_x^2 - d_{31}A_z^3\right)\cos 3\omega t \end{cases} \tag{1}$$