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# An investigation of on-orbit release with inter-satellite electromagnetic force

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ABSTRACT

On-orbit release by inter-satellite electromagnetic force is a novel and valued technology characterized by repetitious release capability, release and re-docking operation integration, no propellant consuming and contamination, etc., thus it ensures a broad prospect of application in future routine on-orbit servicing missions. However, the related issues of dynamics characteristics and guidance control haven't been studied so far. This paper reveals the dynamics characteristics of relative trajectory motion of the "Partner" with respect to its "Master" and presents the principles and guidance control approach for the pre-designed elliptical orbit configuration. The cyclic pursuit theory is utilized to design this guidance controller and its pursuit strategy is designed. In addition, the parameters of the cyclic pursuit controller are tuned in accordance with the requirements of the specific pre-designed elliptical relative motion. The feasibility and performance of the guidance controller are verified by simulation results.

## 1. Introduction

Based on the application of on-orbit release technology, one or more small spacecrafts could be launched from its parent satellite and achieve the "pre-positioned" operations, providing instant responsiveness to on-orbit servicing needs, such as inspection, situational awareness, etc. So far, more than twenty on-orbit release projects have been implemented. The series projects of XSS-10 [1] and XSS-11 [2] released in 2003 and 2005 were both designed to demonstrate the inspection technology within 100 m of other objects. NASA Johnson Space Center has developed a nanosatellite-class free-flyer [3,4] intended for future external inspection and remote viewing of spacecraft, which would be released by an electromagnetic device. In 2007, DARPA demonstrated the on-orbit servicing technology and serviceable capability with Boeing ASTRO and Ball-built NextSat, both of which are on-orbit released in a mated configuration [5,6]. In addition, AFRL launched the ANGELS (Autonomous NanoSatellite Guardian for Evaluating Local Space) project, which was intended to on-orbit release a 20-kg-class spacecraft operating around hosts at geostationary orbit, acquiring space situational awareness capabilities and functionality.

Commonly used on-orbit release devices are thruster and spring system with pyrotechnic operation. However, the actuation of thruster has some inherent disadvantages, such as contamination, propellant consuming, etc. Application of spring system could avoid propellant consuming, but its actuation is one-off, and has large physical impingement and potential explosive hazard with the application of pyrotechnic operation. Nowadays, a novel on-orbit release approach or in other words a novel release device in nature, space electromagnetic release has been preliminarily studied. In 2005, University of Texas developed the EGADS (Electromagnetically Guided Autonomous Docking & Separation) project and accomplished the ground experimental validation. In addition, an on-orbit experiment was also completed in 2006, but without any detailed report [7]. With the project of SLIPP (Secondary Launch Interface/Parasitic Payload), which is a DARPA funded Phase 1 investigation into the viability of using electromagnetic actuators to control the docking and separation between host and drone satellites, University of Montana State constructed a fully functioning demonstration by using an in-house-built electromagnet and a low-friction air track in fall of 2007 [8]. University of Surrey also investigated the design and pose estimation of on-orbit release with inter-satellite electromagnetic force in the ISM (Intelligent, Self-powered Module) mission [9,10]. With the application of inter-satellite electromagnetic force to on-orbit release missions, there is no longer a need for propellant consuming and hazards of physical shock and contamination. Meanwhile, repetitious capability could be acquired which means time after time release operations with same characteristics become possible. In addition, the release and re-docking operations could be accomplished with the same electromagnetic device, and can be safely handed during ground tests, storage and transportation. If related technologies are

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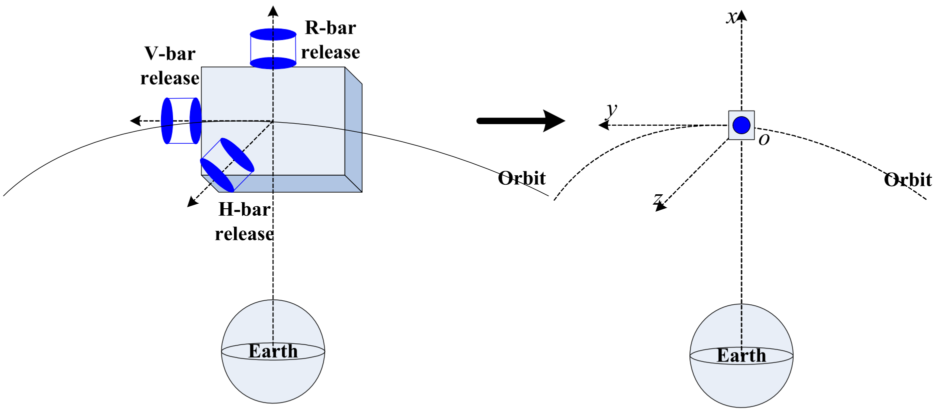

**Fig. 1.** Three elementary on-orbit release scenarios and its mathematical representation.

developed, the on-orbit electromagnetic release technology could find wider applications in fields of departure operation in emergency during space docking, and deployments of solar plane and antennae, etc.

In this manuscript, the dynamics characteristics of on-orbit release with inter-satellite electromagnetic force and the guidance control approach to achieving a pre-defined elliptical relative motion based on cyclic pursuit theory are studied. First, the dynamic models are derived based on the Hill's equation and the far-field electromagnetic force model with proper hypotheses. Second, the dynamics characteristics of on-orbit electromagnetic release in R-bar, V-bar and H-bar are analyzed and put forward, respectively. Third, considering requirements of forming the specified elliptical relative motion, we investigate and derive the guidance control approach based on cyclic pursuit theory, and verify the feasibility of the designed guidance controller by simulation results. Finally, some valued conclusions follow.

## 2. Problem formulation and characteristics

### 2.1. Dynamic models

For simplicity of expression, we used the "Master" and the "Partner" to denote the parent and the servicing satellite, respectively. The on-orbit release mission could be composed by the three elementary release scenarios of R-bar, V-bar and H-bar as in Fig. 1, where their mathematical representations are also present with mass point hypothesis. In this manuscript, we supposed that the attitude control systems both of the "Master" satellite and the "Partner" satellite satisfy all the requirements of release mission.

The far-field analytical mathematical model of inter-satellite electromagnetic force is derived as [11]

$$\boldsymbol{F}(\boldsymbol{\mu}_{\mathrm{M}},\boldsymbol{\mu}_{\mathrm{P}},\boldsymbol{r}_{\mathrm{MP}})=\frac{3\mu_0}{4\pi}\left(-\frac{\boldsymbol{\mu}_{\mathrm{M}}\cdot\boldsymbol{\mu}_{\mathrm{P}}}{r_{\mathrm{MP}}^5}\boldsymbol{r}_{\mathrm{MP}}-\frac{\boldsymbol{\mu}_{\mathrm{M}}\cdot\boldsymbol{r}_{\mathrm{MP}}}{r_{\mathrm{MP}}^5}\boldsymbol{\mu}_{\mathrm{P}}-\frac{\boldsymbol{\mu}_{\mathrm{P}}\cdot\boldsymbol{r}_{\mathrm{MP}}}{r_{\mathrm{MP}}^5}\boldsymbol{\mu}_{\mathrm{M}}+5\frac{(\boldsymbol{\mu}_{\mathrm{M}}\cdot\boldsymbol{r}_{\mathrm{MP}})(\boldsymbol{\mu}_{\mathrm{P}}\cdot\boldsymbol{r}_{\mathrm{MP}})}{r_{\mathrm{MP}}^7}\boldsymbol{r}_{\mathrm{MP}}\right) \tag{1}$$

where $\boldsymbol{\mu}_{\mathrm{M}}$ and $\boldsymbol{\mu}_{\mathrm{P}}$ are magnetic moment vectors of the "Master" and the "Partner" respectively, which will be used to control the relative trajectory motion. $\mu_0$ is permeability of free space and $\boldsymbol{r}_{\mathrm{MP}}$ is the relative distance vector from the "Master" to the "Partner".

Because the relative motions of in-plane and out of plane are decoupled, without loss of generality, we simplified Eq. (1) into $x$–$y$ plane and $z$ axis respectively. A well-suited in-plane electromagnetic force calculation coordinate frame $ox_{\mathrm{C}}y_{\mathrm{C}}$ and the relationship with respect to the orbital frame of the "Master" are depicted as Fig. 2, where $\varphi$ is calculated as

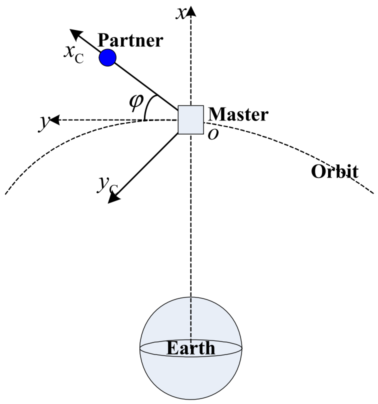

**Fig. 2.** Electromagnetic calculation coordinate frame.

$$\varphi=\arctan 2(x,y) \tag{2}$$

where $x$, $y$ are relative positions of the "Partner" in frame $oxyz$.

The rotation matrix $\boldsymbol{T}^{\mathrm{Co}}$ from frame $ox_{\mathrm{C}}y_{\mathrm{C}}$ to $oxy$ is derived as

$$\boldsymbol{T}^{\mathrm{Co}}=\begin{bmatrix}\sin\varphi & -\cos\varphi & 0\\ \cos\varphi & \sin\varphi & 0\\ 0 & 0 & 1\end{bmatrix} \tag{3}$$

Choosing control variables of the in-plane scenario as $\boldsymbol{u}=[\mu_{\mathrm{M}}\ \alpha\ \mu_{\mathrm{P}}\ \beta]^{\mathrm{T}}$, where $\alpha$, $\beta$ are the rotation angles from $ox_{\mathrm{C}}$ to the directions of $\boldsymbol{\mu}_{\mathrm{M}}$ and $\boldsymbol{\mu}_{\mathrm{P}}$ respectively, the far-field scalar models of electromagnetic force actuated on the "Master" with frame $ox_{\mathrm{C}}y_{\mathrm{C}}$ are derived as [11]

$$\begin{cases}F_{\mathrm{MxC}}=3\mu_0\mu_{\mathrm{M}}\mu_{\mathrm{P}}/(4\pi r_{\mathrm{MP}}^4)(2\cos\alpha\cos\beta-\sin\alpha\sin\beta)\\ F_{\mathrm{MyC}}=-3\mu_0\mu_{\mathrm{M}}\mu_{\mathrm{P}}/(4\pi r_{\mathrm{MP}}^4)(\cos\alpha\sin\beta+\sin\alpha\cos\beta)\end{cases} \tag{4}$$

Based on the internal force characteristics of inter-satellite electromagnetic force, the actuated electromagnetic force on the "Partner" satisfies

$$F_{\mathrm{PxC}}=-F_{\mathrm{MxC}},\qquad F_{\mathrm{PyC}}=-F_{\mathrm{MyC}} \tag{5}$$

As to the independent release in $z$ direction, the control force is constrained into one dimension, as

$$F_{\mathrm{Mz}}=F_{\mathrm{MzC}}=3\mu_0\mu_{\mathrm{M}}\mu_{\mathrm{P}}/(2\pi r_{\mathrm{MP}}^4),\qquad F_{\mathrm{Pz}}=-F_{\mathrm{Mz}} \tag{6}$$

In general, the inter-satellite electromagnetic force simultaneously affects the motions of the "Master" and the "Partner" with