SELF-ORGANIZING SATELLITE CONSTELLATION USING ARTIFICIAL POTENTIAL FIELDS

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Keywords: *swarm, artificial potential field, localized telecoms, autonomous control, self-organizing constellation*

ABSTRACT

As technological advancements in miniaturization continue, the notion of mass-producing functional micro-spacecraft for use in massively distributed constellations is becoming increasingly feasible. Such constellations offer many operational advantages over single-satellite platforms, especially in telecommunications applications where satellite coverage, bandwidth and timing requirements are paramount. Current telecommunications missions provide constant global coverage, regardless of demand. As such, much of the previous research aimed at developing autonomous constellation control strategies have centered on equispaced station-keeping for multi-satellite rings [1, 2]. However, as demand for telecommunications is not uniformly distributed across the Earth's surface, a self-organizing micro-satellite constellation which allocates resources to match demand could demonstrate a more efficient alternative.

Traditional ground-based approaches for control and station-keeping for such large numbers of spacecraft would prove prohibitively complex and expensive. For lower operational costs and increased system flexibility, on-board autonomy is preferred.

This paper presents a control algorithm based on the Artificial Potential Field (APF) method for autonomous reconfiguration of a micro-satellite constellation in Earth-centered orbits for re-allocating satellite resources to match demand on the Earth's surface. An APF is constructed as a function of the Keplerian elements of each satellite and the mean inter-satellite phasing, $\bar{\phi}$, defined as the mean phasing difference between adjacent satellites. The APF is designed with two terms: an attractive term V_{kep_i} acts to maintain the satellites at the desired operational orbit once reached, a second term defines the phasing requirements. This can switch between equal mean anomaly spacing between the satellites (V_{ϕ_i}) and concentrating the satellites over particular regions on the Earth's surface (V_{ξ_i}). In equal mean anomaly spacing mode, each satellite exerts an equal virtual repulsive force on all other satellites, causing them to settle into an equispaced configuration. When the control is switched to the localized concentration mode, instead, a virtual repulsive potential field is inserted into the swarm model at 180° from the phasing location of the target on the Earth's surface. This APF exerts a repulsive force of a greater magnitude than that of the inter-satellite potentials, causing them to autonomously concentrate above the target location. Additionally, alternative forms of the localized potential field are investigated and compared. The potential of the overall system, V_{sys}, is shown to monotonically decrease, and is defined by

$$V_{\text{sys}} = \sum_{i}^{N} V_{\text{sc}i} \tag{1}$$

Each satellite potential, V_{sc}, has the following form

$$V_{\text{sc}i} = V_{\text{kep}_i} + V_{\phi_i} + V_{\xi_i} \tag{2}$$

where subscripts kep, ϕ and ξ denote the orbital element, phasing angle, and coverage controllers, respectively.

Commands to generate control actions for each spacecraft, $\Delta\mathbf{v}_i$, are then generated based on the direction of steepest descent of the APF determined from the gradient of the APF with respect to the spacecraft velocities using Lyapunov stability theory, as according to Equation 3.

$$\Delta\mathbf{v}_i = -\exp\left(\lambda V_{\text{sys}}\right)\frac{\nabla V_{\text{sys}}}{\left|\left|\nabla V_{\text{sys}}\right|\right|} \tag{3}$$

The model assumes that the spacecraft has thrusting capabilities in the tangential and normal directions. The Gauss planetary equations are used in the control algorithm and for orbit propagation, including the effects of orbit perturbations such as the J_2 effect and aerodynamic drag.

Through the proposed control algorithm a telecommunications mission is designed. A constellation of N satellites is placed in Low Earth Orbit at a 400 km altitude, initially equispaced. The constellation then senses increased local telecommunications demand on the Earth's surface. When the self-organizing term of the APF is activated, the constellation autonomously reconfigures to service this demand. The constellation convergence time and propellant requirements are analyzed, and optimal gain values for the APF are determined. The constellation is shown to reconfigure to meet the modified coverage/bandwidth requirements. In a second case, the total Δv for the system reconfiguration is minimized by timing each spacecraft's maneuvers in each orbit.

Preliminary results show that the equispaced (Fig 1) and the concentrated (Fig 2) modes both operate successfully with a constellation of 10 satellites converging within an time.

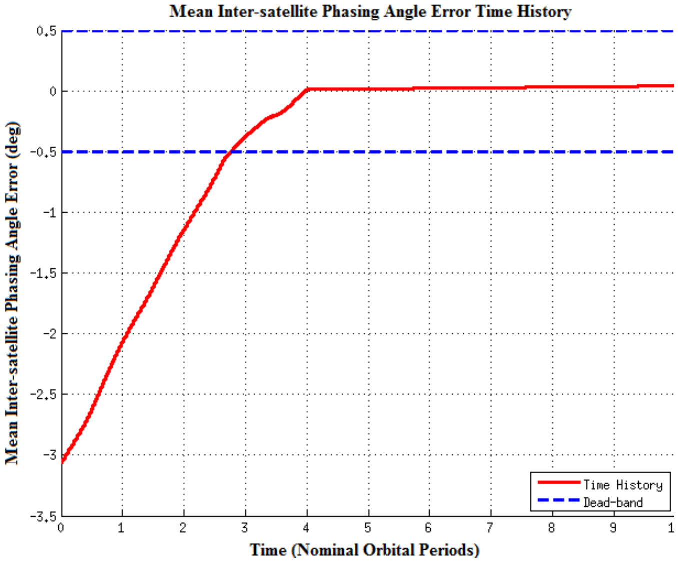

Figure 1. $\bar{\phi}$ **in equispaced mode**

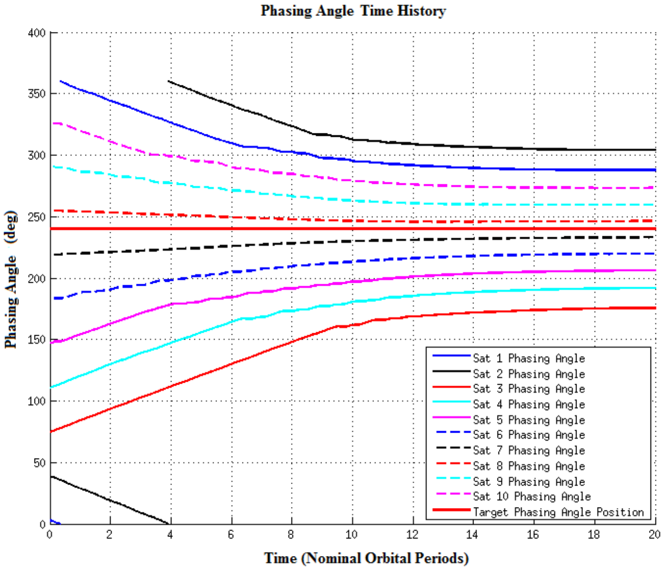

Figure 2. Phasing angles in concentrate mode

References

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