Parallel Thruster–Propeller Control for Emulating Spacecraft Proximity Dynamics on a Free-Flyer

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1. Introduction

Motivation

Air-bearing free-flyers simulate spacecraft dynamics by reproducing near-frictionless planar motion, but do not inherently reproduce orbital proximity dynamics (rendezvous, docking, formation flight).

Using the platform's own thrusters to emulate those dynamics couples maneuvering with environment emulation, limiting fidelity.

We present a dual-actuation architecture that emulates these dynamics, the linearized Clohessy–Wiltshire (CW) equations, on a free-flyer without that coupling.

Contributions

(1) Dual-actuation architecture: two parallel controllers emulate orbital dynamics on a free-flyer, the dynamics reference continuously updated for spacecraft thrust.

(2) Propeller module: continuous, proportional thrust as a new ATMOS modality for injecting orbital dynamics, disturbances, or other forces.

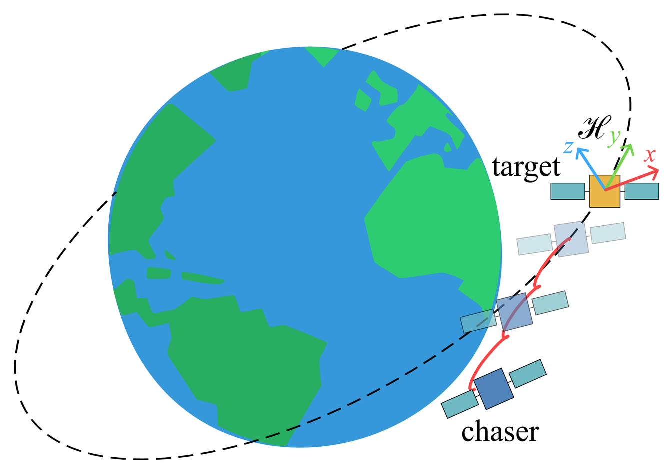
2. Spacecraft Proximity Dynamics

Relative motion of a chaser about a target on a circular orbit, in the target-centred Hill frame (radial x, along-track y):

$$\begin{aligned}\ddot{p}_x &= 3n^2 p_x + 2n\,\dot{p}_y + F_x/m,\\ \ddot{p}_y &= -2n\,\dot{p}_x + F_y/m,\end{aligned} \tag{1}$$

with mean motion $n = 2\pi/T$.

As a result, a chaser will drift relative to the target under CW dynamics if not compensated.



Unforced, CW has a closed-form solution:

$$\begin{bmatrix}\boldsymbol{p}(t)\\ \boldsymbol{v}(t)\end{bmatrix} = \begin{bmatrix}\boldsymbol{\Phi}_{pp}(t) & \boldsymbol{\Phi}_{pv}(t)\\ \boldsymbol{\Phi}_{vp}(t) & \boldsymbol{\Phi}_{vv}(t)\end{bmatrix}\begin{bmatrix}\boldsymbol{p}_0\\ \boldsymbol{v}_0\end{bmatrix}, \tag{2}$$

with $c = \cos(nt)$, $s = \sin(nt)$, and

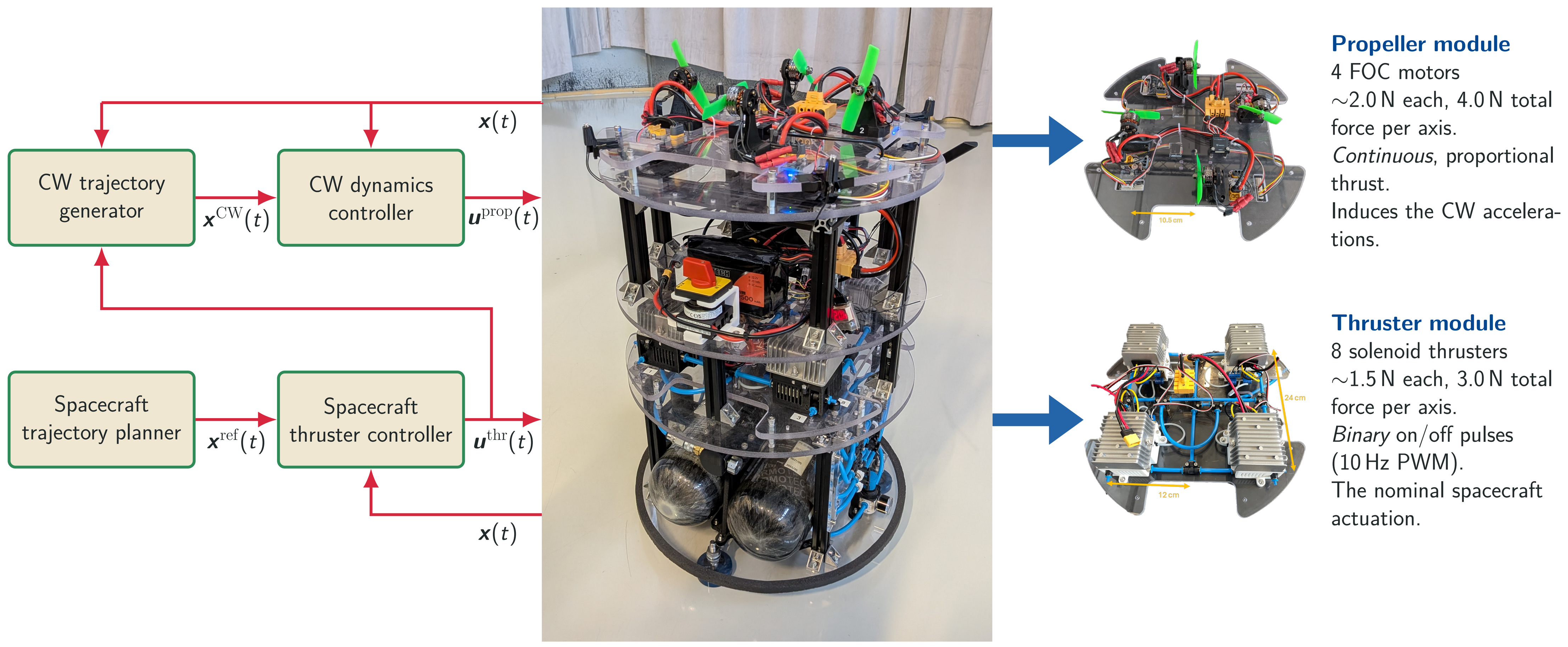
$$\begin{aligned}\boldsymbol{\Phi}_{pp} &= \begin{bmatrix}4-3c & 0\\ 6(s-nt) & 1\end{bmatrix}, \quad \boldsymbol{\Phi}_{pv} = \frac{1}{n}\begin{bmatrix}s & 2(1-c)\\ 2(c-1) & 4s-3nt\end{bmatrix},\\ \boldsymbol{\Phi}_{vp} &= n\begin{bmatrix}3s & 0\\ 6(c-1) & 0\end{bmatrix}, \quad \boldsymbol{\Phi}_{vv} = \begin{bmatrix}c & 2s\\ -2s & 4c-3\end{bmatrix}.\end{aligned} \tag{3}$$

An unforced CW trajectory is thus defined entirely by n, $\boldsymbol{p}_0$, and $\boldsymbol{v}_0$.

3. Closed-Loop Parallel Control Architecture

Hardware

We extend the open-source ATMOS free-flyer (`atmos.discower.io`) with a new propeller module. The state feedback is obtained by fusing external motion capture with onboard inertial sensing, and vehicle state and command messages are exchanged over ROS 2.



ATMOS free-flyer

Control architecture

Both controllers are nonlinear MPCs sharing the same optimal-control problem formulation and state vector $\boldsymbol{x} = [\boldsymbol{p}\ \boldsymbol{v}\ \mathbf{q}\ \omega]$, differing only in their dynamics model $f(\boldsymbol{x},\boldsymbol{u})$, control input $\boldsymbol{u}$, and reference $\boldsymbol{x}^{\mathrm{ref}}/\boldsymbol{x}^{\mathrm{CW}}$:

$$\begin{aligned}J^*(\boldsymbol{x}_k) = \min_{\boldsymbol{u}_k}\ &\textstyle\sum_{n=0}^{N-1} \ell(\boldsymbol{x}(n|k),\boldsymbol{u}(n|k)) + \ell_N(\boldsymbol{x}(N|k))\\ \text{s.t.}\quad &\boldsymbol{x}(0|k) = \boldsymbol{x}_k, \quad \boldsymbol{x}(n{+}1|k) = f(\boldsymbol{x}(n|k),\boldsymbol{u}(n|k)),\\ &\boldsymbol{x}(n|k) \in \mathbb{X}, \quad \boldsymbol{u}(n|k) \in \mathbb{U}.\end{aligned} \tag{4}$$

Spacecraft thruster controller
Free-floating dynamics *augmented* with the CW acceleration $\boldsymbol{a}^{\mathrm{CW}}$ (unforced eq. (1)), compensating for the relative drift in orbit:

$$\begin{aligned}\dot{\boldsymbol{p}} &= \boldsymbol{v}, & \dot{\boldsymbol{v}} &= \boldsymbol{a}^{\mathrm{CW}}(\boldsymbol{p},\boldsymbol{v}) + \tfrac{1}{m}\mathrm{R}(\mathbf{q})\,\boldsymbol{F}^{\mathrm{thr}},\\ \dot{\mathbf{q}} &= \tfrac{1}{2}\boldsymbol{\Omega}(\omega)\,\mathbf{q}, & \dot{\omega} &= \mathbf{J}^{-1}\big(\boldsymbol{\tau}^{\mathrm{thr}} - \omega\times\mathbf{J}\omega\big).\end{aligned} \tag{5}$$

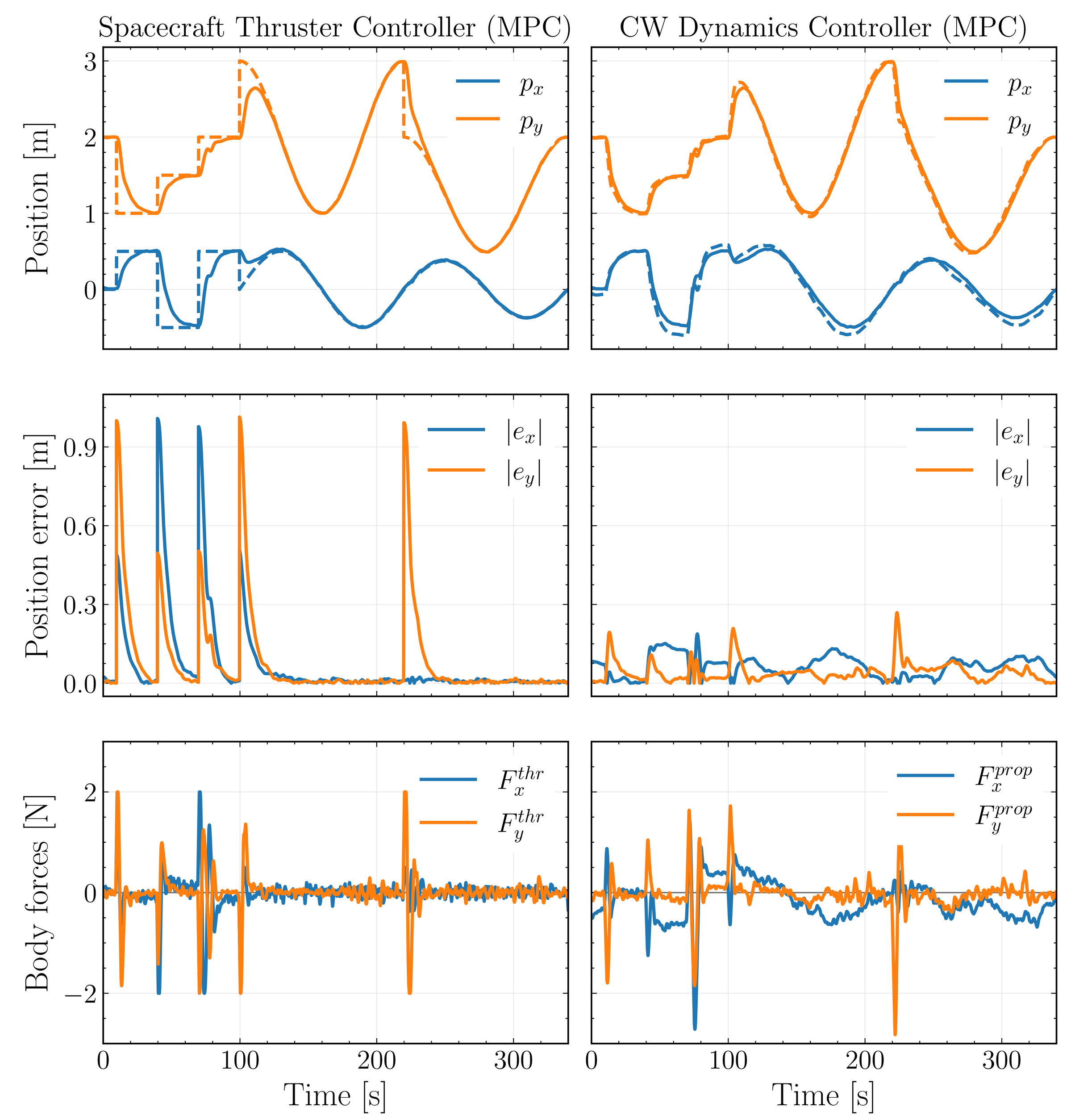
CW dynamics controller (propellers)
The *same* model *without* the $\boldsymbol{a}^{\mathrm{CW}}$-term (pure free-floating dynamics), physically injecting $\boldsymbol{a}^{\mathrm{CW}}$ through its reference trajectory.
The CW trajectory is generated from the closed-form CW-solution (eq. (2)), and continuously updated with each thruster command as:

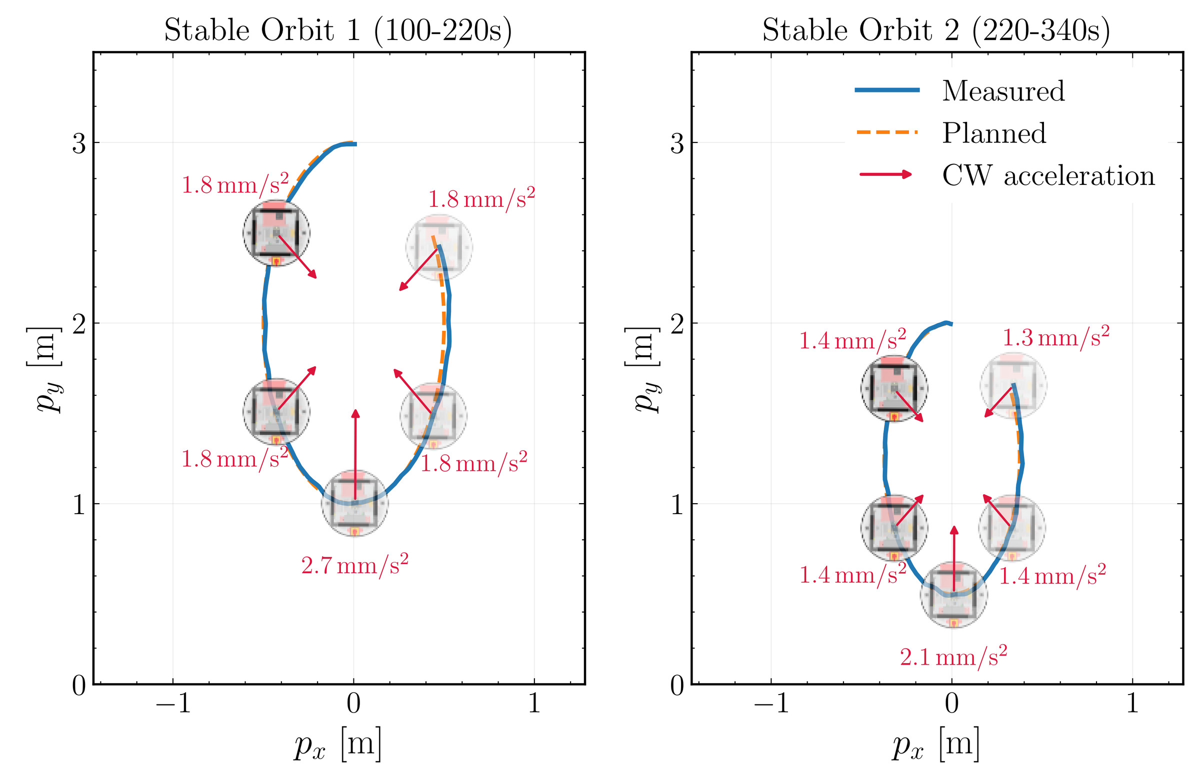
$$\boldsymbol{p}_0 \leftarrow \boldsymbol{p}^-(t), \quad \boldsymbol{v}_0 \leftarrow \boldsymbol{v}^-(t) + \Delta\boldsymbol{v}, \quad \Delta\boldsymbol{v} = \tfrac{1}{m}\mathrm{R}(\mathbf{q})\,\boldsymbol{F}^{\mathrm{thr}}\,\Delta t, \tag{6}$$

where $\boldsymbol{p}^-(t), \boldsymbol{v}^-(t)$ are the prior closed-form solutions.

4. Experimental Results

The approach is evaluated using a down-scaled orbital period of $T = 2$ min. *Phase 1:* hold three *unstable* setpoints. *Phase 2:* track two *stable* relative orbits (satisfying the drift-free condition $v_{y,0} = -2n\,p_{x,0}$).





The thruster controller tracked the preplanned spacecraft trajectory closely, with position errors converging to less than 20 mm.

During the stable orbit, the propellers delivered a slowly varying force of ± 0.6 N, while the thrusters fired only in short corrective bursts of ± 0.15 N.

Watch the experiment

5. Summary & Future Work

We made a spacecraft-analog platform physically experience relative orbital dynamics! One controller flies the "spacecraft" with thrusters; a second uses propellers to physically apply the orbital forces. Experiments show close tracking with the two actuation roles cleanly decoupled.

Future work: Sensitivity in scaling parameters; Simultaneous attitude maneuvers; Validation against high-fidelity orbital simulators; Active compensation of disturbances and modeling errors; Multi-agent proximity operations.