On Track: Path Following Controller Designs for **Autonomous** and **Semi-Autonomous** Industrial **Motor Graders**

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Introduction

This paper introduces **Single Track Control** (STC), a control methodology that enables existing automation techniques for centre-articulated vehicles to be applied to industrial motor graders.

Motor Graders are heavy machinery used to smooth, or grade, road surfaces at mine sites with a moldboard (blade). This operation is crucial for **mine safety** and **efficiency.** However, complex terrain interactions, 6-DoF moldboard control, and **redundant steering kinematics** resulting from frame articulation and front wheel steering have complicated automation efforts.

Single Track Control leverages the redundancy to impose that the **rear wheels follow the same track (path) as the front wheels**, like other centre-articulated mining vehicles – i.e. Load Haul Dump (LHD) or haulage trucks.

We designed STC-enabled controllers, and performed a tuning analysis in simulation to assess viability of the methodology as proof-of-concept.

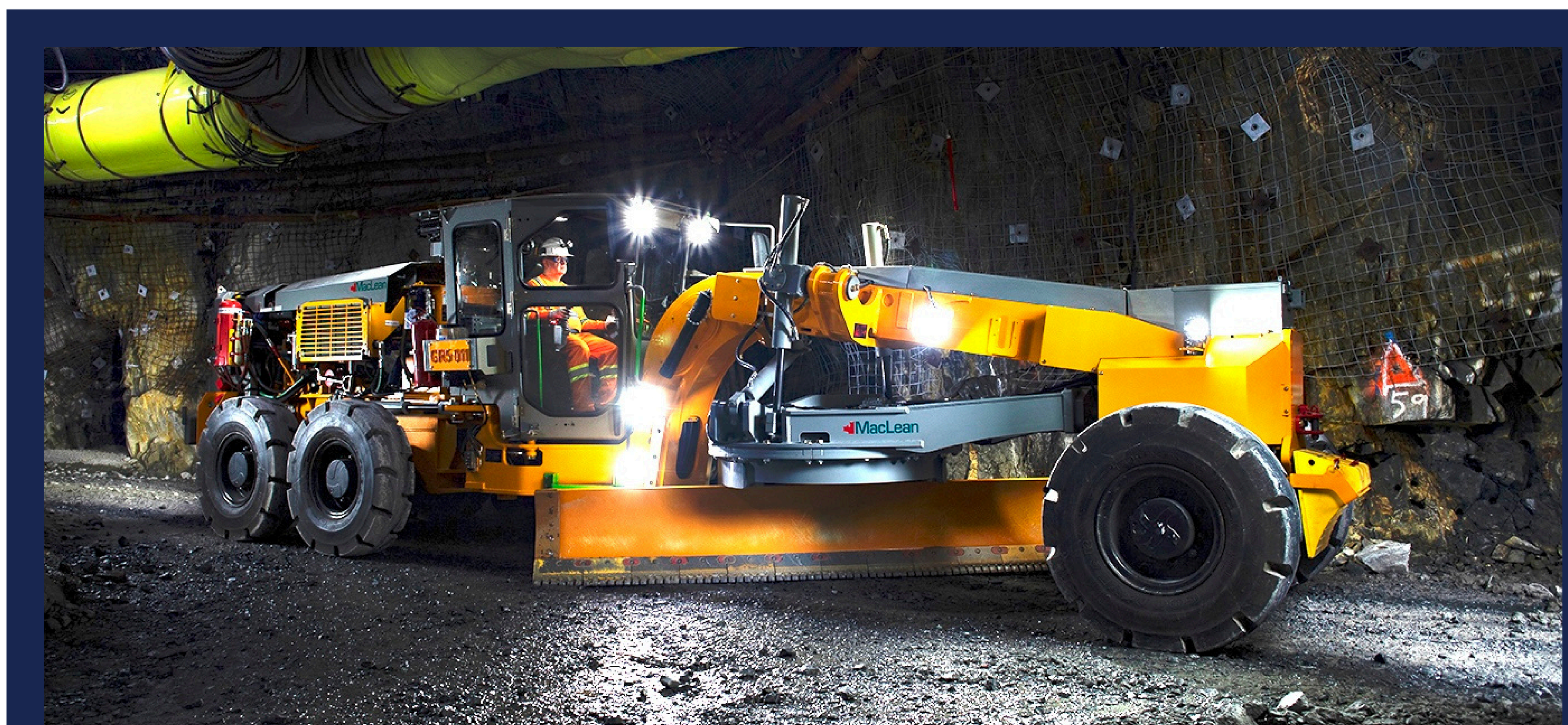

Photo credit: MacLean Engineering, "MacLean GR5 Grader EV," MacLean Engineering, [Online]. Available: https://macleanengineering.com/product/maclean-gr5-grader-ev/. [Accessed: May 22, 2025].

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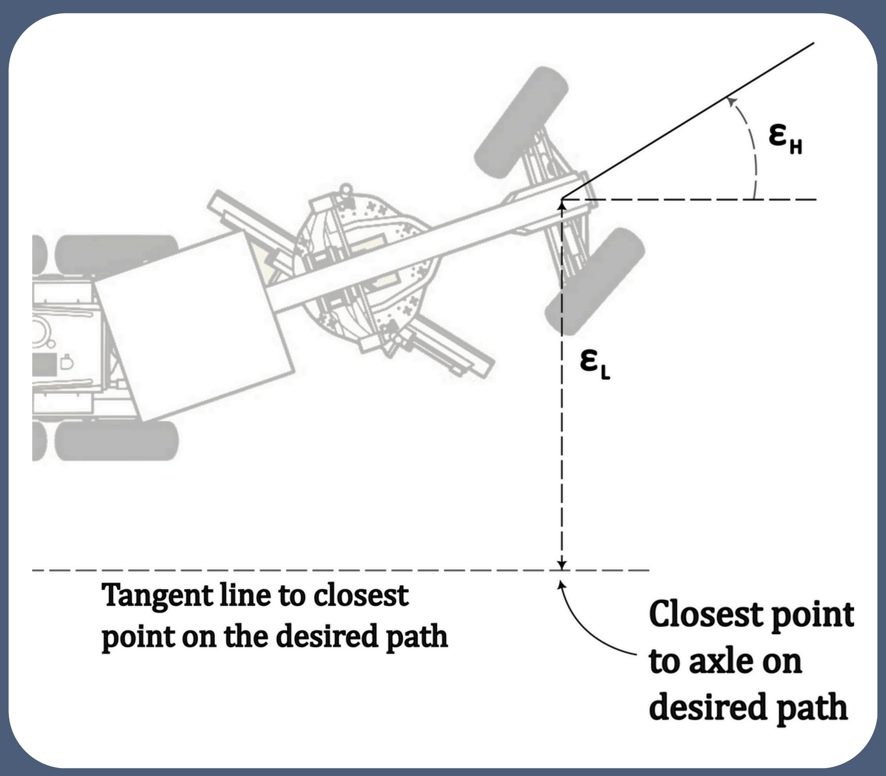
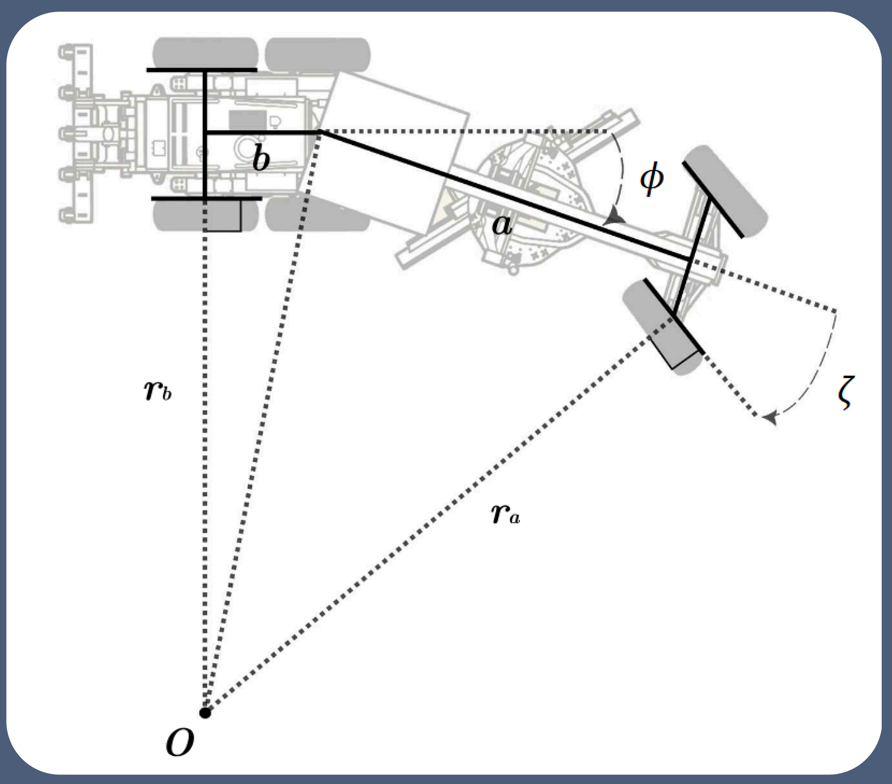
Control Design

We derive **vehicle kinematics,** and apply extend existing techniques to evaluate **feedback linearized + single track controllers (FBL+STC)**. To resolve kinematic redundancy, we:

- v_1: maintain a constant linear speed
- v_2: obtain desired articulation rate with an **FBL controller** (PD, 2x MPC), [2]
- v_3: solve for the corresponding steering angle to satisfy **STC**





We define lateral and heading errors for the front wheels, and chain for the FBL error system

$$\begin{bmatrix}\dot z_1\\ \dot z_2\end{bmatrix} = \begin{bmatrix}\dot\varepsilon_L\\ \ddot\varepsilon_L\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}z + \begin{bmatrix}0\\ 1\end{bmatrix}\eta$$

then unwarp FBL input η for articulation rate v_2,

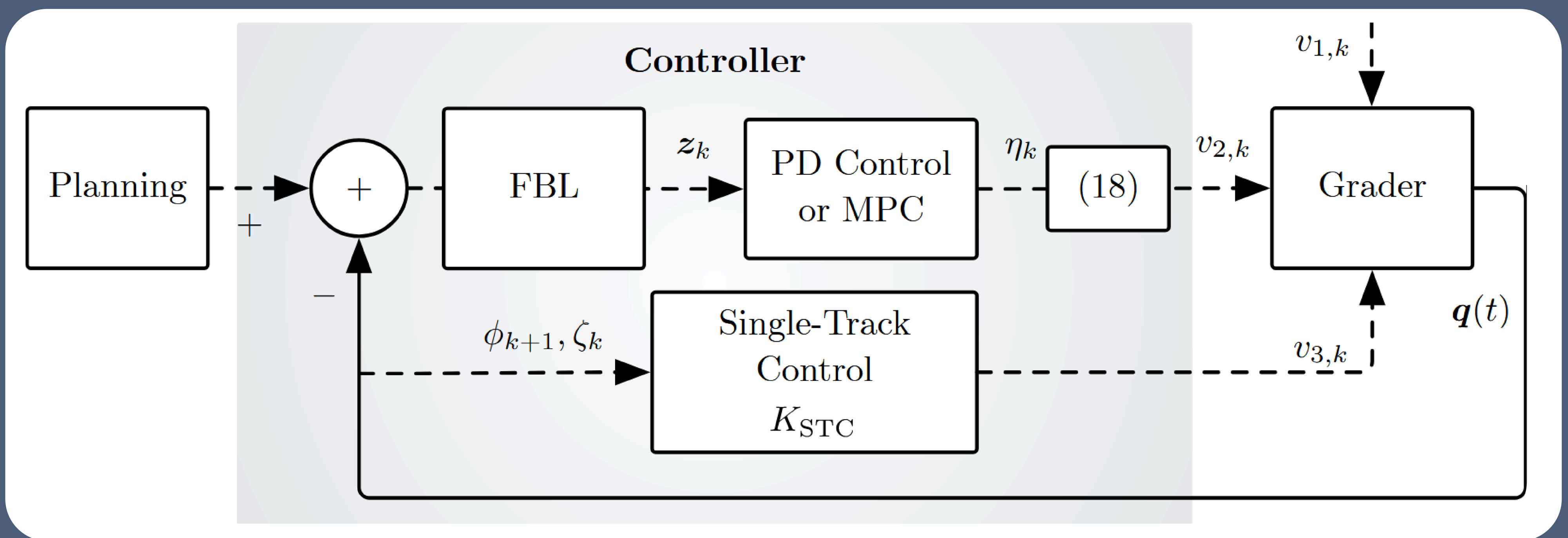
$$v_2 = \frac{b}{a\cos(\phi) + b}\left(\frac{\eta}{v_1\cos(\varepsilon_H)}\right)$$

With ϕ_d selected by FBL, we choose ζ such that $r_a = r_b$, obtaining

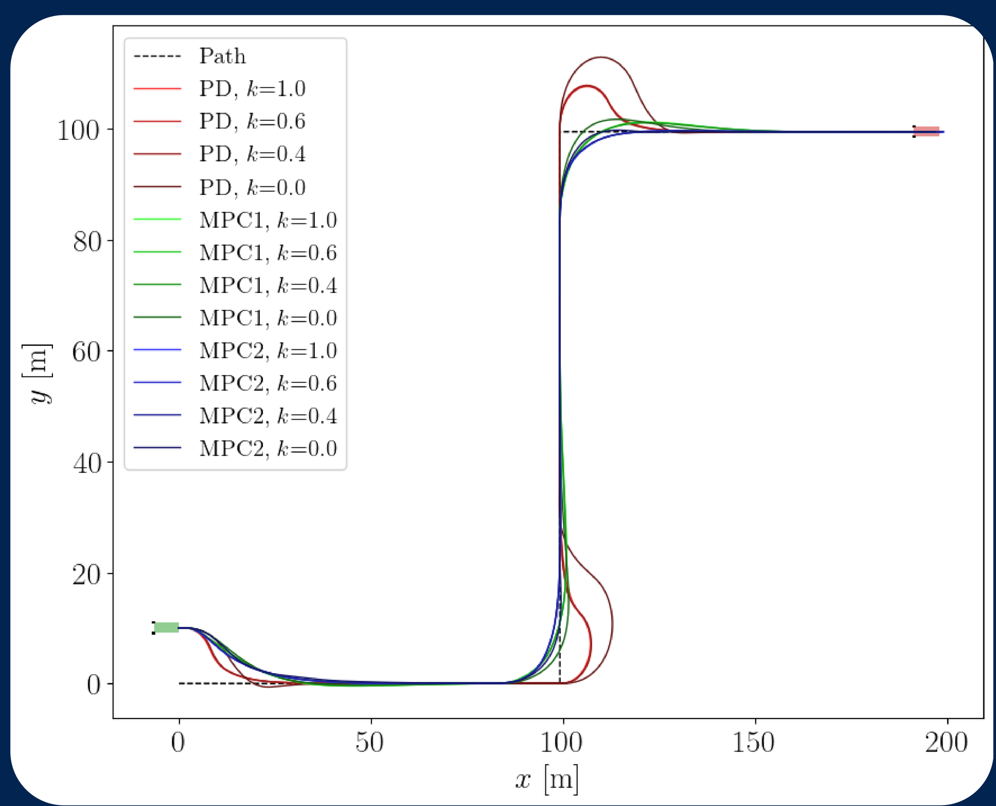
$$\frac{b}{a} = \frac{\cos(\phi) - \cos(\zeta)}{\cos(\phi + \zeta) - 1}$$

A 1st order controller tracks ζ_d, varying the effect of the plant-model mismatch.

Note: STC is not separable; a numerical method is used to converge to a solution.



Results



Selected controller comparison. Error was measured as RMSE of path following errors; effort was measured as the L^2 norm of rate inputs.

Controller	k_{STC}	Parameters	RMSE	Effort
FBL+PD	0.0	$\omega_n = 1.63$, $\zeta = 1.03$	1310	6.19
STC+FBL+PD	1.0	$\omega_n = 1.63$, $\zeta = 1.03$	668	5.50
FBL+MPC1	0.0	$q = 22.7$, $r = 1.89$	580	2.97
STC+FBL+MPC1	0.4	$q = 11.4$, $r = 4.29$	614	2.34
FBL+MPC2	0.0	$q = 2.16$, $r = 4.78$	465	3.35
STC+FBL+MPC2	1.0	$q = 0.239$, $r = 5.19$	477	2.46

A tuning analysis was done to analyze the performance of STC-enabled controllers (one PD, two MPC). Results indicate that **comparable path-following performance, with reduced actuator effort in all cases**, indicating promise for field applications.

Future work includes addressing the plant-model mismatch, simulation under dynamic disturbances, and field experiments.

Benefits of STC

Practically, STC presents three main benefits:
1) **improved safety and manoeuvrability** for navigating underground drifts,
2) existing techniques for centre-articulated vehicles can be extended to **autonomous** operation of motor graders, and
3) STC consolidates steering as a single input, reducing the need for specialized training in **semi-autonomous** applications.

[1] A. Beca and J. A. Marshall, "Path following controller designs for autonomous and semi-autonomous industrial motor graders," Proc. Conf. Robots and Vision (CRV), Calgary, AB, Canada, 2025
[2] J. A. Marshall, T. D. Barfoot, and J. Larsson, "Autonomous underground tramming for center-articulated vehicles," J. Field Robot., vol. 25, no. 6-7, pp. 400–421, Jun. 2008.

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