Autonomous Farming: Closed-Loop Estimators

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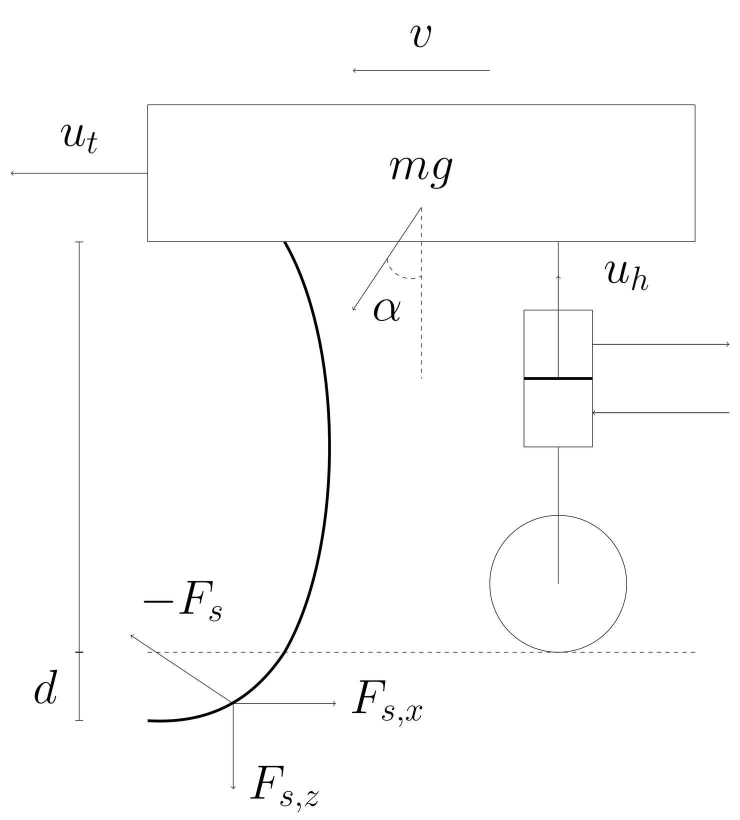
Background

Agriculture faces global challenges such as biodiversity loss, climate change, and population growth. Sustainable food production demands higher efficiency despite limited land, labor shortages, and stricter regulations. Autonomous farming machinery offers a path forward. This work investigates how to control soil cultivation machines during unknown soil conditions.

The Autonomous Cultivation Problem

Soil and tool interaction is nonlinear, variable, and unmeasurable, posing challenges for both modeling and control. The goal is to design controllers that maintain desired working depth and reaction forces, despite unknown and spatially varying soil conditions, while simultaneously



estimating the soil condition function for use in feed-forward control. The soil interaction force is in this work modeled as:

$$F_s = A(d)\, v^2\, K(p), \qquad K(p) = \boldsymbol{\theta_0}^\top \boldsymbol{r}(p),$$
$$\boldsymbol{r}(p) = \left[p_x^2\ p_x p_y\ p_x\ p_y^2\ p_y\ 1\right]^\top$$

Using Euler discretization of the speed dynamical equation gives a regression model relation

$$y(t) = \boldsymbol{\theta_0}^\top \varphi(t) + e(t),$$

where y is constructed from measured (v, d, α) and inputs (u_t), and $\varphi(t) = w_t\, d(t)\, v^2(t)\, \boldsymbol{r}(p(t))$. With measurement/process noise in both y and φ, the error $e(t)$ correlates with $\varphi(t)$:

$$\bar{E}\{\varphi(t)e(t)\} \neq 0 \ \Rightarrow\ \hat{\boldsymbol{\theta}}_\infty^{\text{LS}} \neq \boldsymbol{\theta}_0 \text{ (biased).}$$

To cope with the bias the instrumental variables method is used. Choosing instruments $\xi(t)$ such that

$$\bar{E}\{\xi(t)\varphi^\top(t)\} \text{ full rank}, \qquad \bar{E}\{\xi(t)[y(t) - \boldsymbol{\theta}^\top\varphi(t)]\} = 0.$$

results in the asymptotic IV estimate

$$\hat{\boldsymbol{\theta}}_\infty^{\text{IV}} = \bar{E}\{\xi(t)\varphi^\top(t)\}^{-1}\bar{E}\{\xi(t)y(t)\} \ \Rightarrow\ \hat{\boldsymbol{\theta}}_\infty^{\text{IV}} = \boldsymbol{\theta}_0.$$

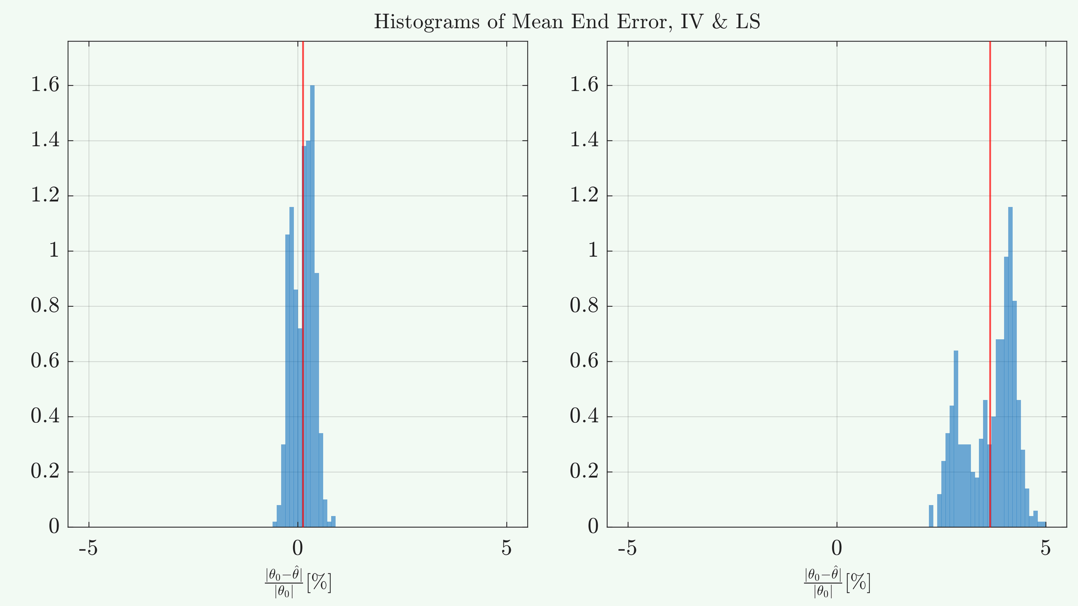
To get accurate estimates, a *nominal*, noise-free model (known structure, unknown field conditions) can be simulated to generate $(\bar{v}, \bar{d})$ and set

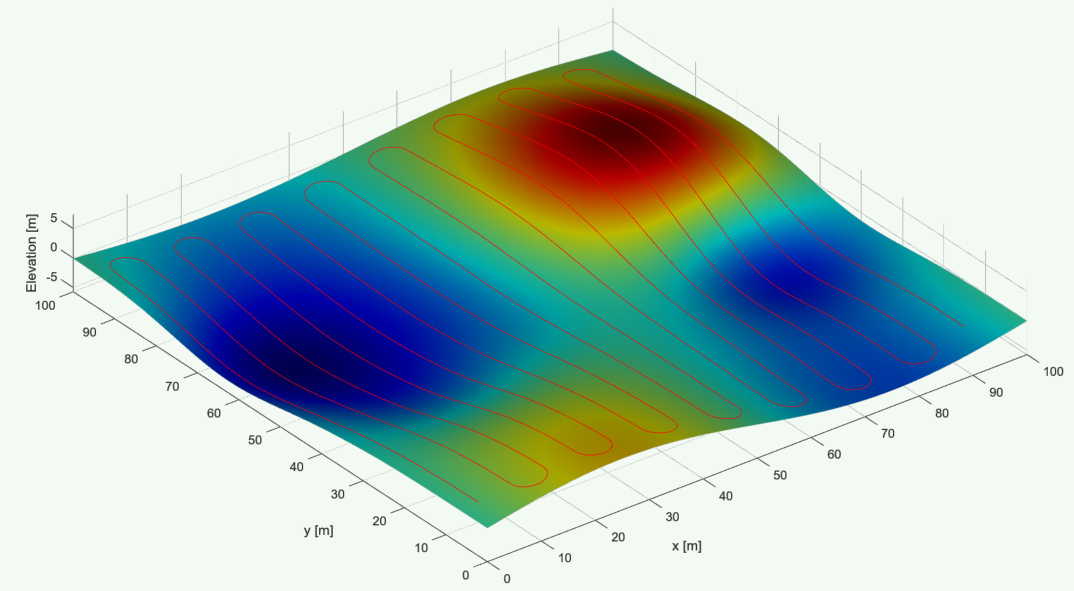
$$\xi(t) = \bar{d}(t)\,\bar{v}^2(t)\,\boldsymbol{r}(p(t)) - \frac{1}{t}\sum_{k=1}^{t} \bar{d}(k)\,\bar{v}^2(k)\,\boldsymbol{r}(p(k)),$$

which enforces the instruments to be zero-mean and eliminates error correlation.

Simulation results

The system was simulated over arbitrary elevated fields 500 times for each method with both Gaussian distributed noise terms and true parameter set $\boldsymbol{\theta}_0$.





Relation to SEDDIT focus area

Zero carbon emissions:

- Increased fuel efficiency, no unnecessary cultivation
- Efficient cultivation → limited soil emissions.

Societal security and environmental monitoring:

- Resilient food production
- Soil condition monitoring gives precision farming possibilities.

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